

**NASA TECHNICAL  
MEMORANDUM**

**NASA TM X-53346**

**October 18, 1965**

**NASA TM X-53346**

FACILITY FORM 802	<b>N66-14781</b>	
	(ACCESSION NUMBER) <u>70</u>	(THRU) <u>1</u>
	(PAGES)	(CODE) <u>33</u>
	(NASA CR OR TMX OR AD NUMBER)	
		(CATEGORY)

**A SET OF EXPERIMENTS IN THERMAL SIMILITUDE**

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Hard copy (HC) 3.00

Microfilm (MF) .75

11-653 (11) P

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RESEARCH AND DEVELOPMENT OPERATIONS

## ACKNOWLEDGMENTS

The Arnold Engineering Development Center/ARO, Inc. fabricated the models and carried out the experiments in their facilities according to detailed specifications furnished by the Research Projects Laboratory, Marshall Space Flight Center.

Mr. Emerson Whatley, Scientific Programming, General Electric Company/Computation Laboratory, Marshall Space Flight Center, programmed the analysis of the experimental data on the IBM 7090 computer and the automatic plotting on the Stromberg-Carlson SC 4020 plotter.

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## NOMENCLATURE

- $C_j$  = heat capacity of jth region  
 $T_j$  = temperature of jth region  
 $T_k$  = temperature of kth region  
 $(\dot{T}_j)$  = derivative of  $T_j$  with respect to time)  
 $C_{kj}$  = over-all conduction coefficient between regions k and j  
 $R_{kj}$  = over-all radiant coefficient for net radiative transfer from region k to j  
 $q_j$  = internal power dissipation in the jth region  
 $^sA_j$  = effective area of surface j to sun  
 $A_j$  = total area of surface j radiating to space  
 $\epsilon_j$  = infrared emissivity of surface j  
 $\alpha_j$  = absorptivity of surface j with respect to solar insolation  
 $S$  = solar constant  
 $\sigma$  = Stefan-Boltzmann constant  
 $F_{kj}$  = classical geometry factor for net radiation exchange based on Lambert's cosine law for diffuse radiation  
 $d, b, r_1, r_2, r_3, r_4, L, W, h$  = particular linear dimensions (Fig. 2)  
 $k_j$  = thermal conductivity of jth region  
 $(\rho c \rho_j)$  = density-specific heat product for jth region (volumetric heat capacity)  
 $H_j$  = solar radiation and internal generation ( =  $q_j + \alpha_j^s A_j S$  )  
 $t$  = time

## TECHNICAL MEMORANDUM X-53346

### A SET OF EXPERIMENTS IN THERMAL SIMILITUDE

#### SUMMARY

The analysis and results for two sets of experiments in thermal scale modeling are presented. The prototype and model consist of a plate, cylinder, and sphere exchanging thermal energy by radiation only. They were located relative to one another in an unsymmetrical arrangement.

The experimental results generally confirm the modeling rules, with some exceptions in the details, due largely to an a priori assumption made regarding the volume partitioning of the objects to be modeled.

## INTRODUCTION

Previously derived scale modeling laws [1] were used as the basis for the design of experiments in thermal similitude. The purpose of the experiments was to test the theoretical laws for the transient case where several bodies with geometrical shapes common to space vehicles exchange energy solely by thermal radiation. The three bodies, a sphere, a cylinder, and a flat plate, were in a particular asymmetrical, geometrical arrangement (Figure 1).

Experiments were conducted on both a full-scale prototype and a model, since the primary objective was to test the scaling laws. The main overall dimensions of the prototype were scaled a priori by  $\frac{1}{2}$  and minor dimensions were deliberately distorted to satisfy the scaling relations.

An important secondary objective of the experiments was to discover practical difficulties in modeling and to develop techniques to overcome them.

Analysis for the comparison of the prototype and model temperatures was made on an IBM 7090 computer, and the graphs were machine plotted using a Stromberg-Carlson SC 4020 plotter.

Some modeling work done by Adkins that is very similar to this has been reported in the literature [2] .

This report includes two sets of experiments which were conducted several months apart.

## DESCRIPTIVE EQUATIONS

Since there was no conductive or convective heat exchange between the objects, only radiative exchange will be considered. They are assumed to be exposed to external radiation equivalent to solar radiation and to have heat dissipated internally. Part of the objective was to use the crudest possible physical partition of the bodies in order to determine the limits on crudeness for modeling. Toward this end, each object is represented by a single temperature. The difference equations describing their transient behavior under these conditions are [3]

$$C_j \frac{\Delta T_j}{\Delta t} = \sum_{k=1, k \neq j}^4 R_{kj} (T_k^4 - T_j^4) + q_j + \alpha_j^s A_j S, \quad (j=1, 2, 3) \quad (1)$$

and

$$\frac{\Delta T_4}{\Delta t} = 0, \quad T_4 = \text{constant},$$

since  $T_4$  represents the chamber wall, which is maintained with liquid nitrogen at a fixed temperature.

## SCALING RELATIONS AND MODEL DESIGN

The general similarity criteria which includes this special case is given by Eq. (4) in Reference [1]. From this list, with the additional definition

$$H_j = q_j + \alpha_j^s A_j S, \quad j = 1, 2, 3. \quad (2)$$



the following independent set of scaling ratios is obtained:

$$\frac{T_j}{T_k}, \frac{\epsilon_j \sigma A_j T_j^3 t}{C_j}, \frac{R_{kj} T_j^3 t}{C_j}, \frac{H_j t}{C_j T_j}. \quad (3)$$

If electrical resistance heaters are used to obtain the simulated heating effects of solar insolation, and if the space chamber is regarded as incorporated in the third ratio with its appropriate exchange coefficient, then the modeling ratios for the problem are

$$\frac{T_j}{T_k}, \frac{R_{kj} T_j^3 t}{C_j}, \frac{q_j t}{C_j T_j} \quad (j, k = 1, \dots, 4). \quad (4)$$

The detailed dimensional notation used is shown in Figure 2. All major external dimensions are scaled by  $\frac{1}{2}$ . It is assumed that the materials are not changed from prototype to model, that the radiation geometry factors remain unchanged, that the temperatures of the model at a particular time are equal to the corresponding prototype temperatures at the same time, and that the thickness of the cylinder end caps are not changed from prototype to model. These a priori requirements are

$$\begin{aligned} T_j^* &= T_j & t^* &= t & (\rho c \rho)_j^* &= (\rho c \rho)_j \\ L^* &= \frac{1}{2} L & r_2^* &= \frac{1}{2} r_2 & h^* &= \frac{1}{2} h \\ F_{kj}^* &= F_{kj} & W^* &= \frac{1}{2} W & r_4^* &= \frac{1}{2} r_4 \\ b^* &= b \end{aligned} \quad (j = 1, 2, 3) \quad (5)$$

These requirements, together with the scaling laws [4], impose geometric distortion in the minor dimensions. The results, summarized in Table I, were used as the basis for the detailed model design.

It is economical to fabricate whenever possible from standard gage material. However, review of the modeling rules in Table I reveals that the minor dimension distortions (thicknesses) constitute one of the main aspects. In addition, standard gage thicknesses have an average tolerance of  $\pm 0.005$  inches, ( $1.27 \times 10^{-4}$  meters) and there is often non-uniformity within a particular stock sheet. To minimize these difficulties, it was decided that the larger objects (prototype) would be fabricated from gage stock, but that the thicknesses of the stock sheet used would be measured to the smallest possible tolerance prior to use. Then, these measured thicknesses would be used in the modeling relations to predict the dimensions required for the models. The models, which are small, would then be fabricated by machining and milling to the tolerance of  $\pm 0.001$  inch ( $2.54 \times 10^{-5}$  meters). This appeared to be the most economical approach without compromising the modeling laws. The resulting dimensions are shown in Table II.

Electrical resistance heaters were used to represent internal dissipation and solar insolation on the plate. The heat capacity of the heater would upset the modeling criteria if it is relatively large compared to the heat capacity of the plate. Devices for attaching the heater to the plate also contribute substantially to the heat capacity of the system. However, the heater in all its aspects could also be modeled. It was decided that it would be best to represent the plate by two parallel sheets, each having equal thickness. The heater would then be mounted between the plates by carefully designed connectors, and the heater

TABLE I  
Explicit Modeling Criteria

Quantity	Model/Prototype	Remarks
$T_j$	1	a priori determined
$t$	1	a priori determined
$F_{kj}$	1	a priori determined
$(\rho c \rho)_j$	1	a priori, material property
$L$	$\frac{1}{2}$	a priori, major dimension
$W$	$\frac{1}{2}$	a priori, major dimension
$r_2$	$\frac{1}{2}$	a priori, major dimension
$r_4$	$\frac{1}{2}$	a priori, major dimension
$h$	$\frac{1}{2}$	a priori, major dimension
$q_j$	$\frac{1}{4}$	-----
$d$	1	distorted (derived)
$b$	1	distorted (a priori)
$r_1$	$\frac{1}{4}k_1$	distorted (derived)
$r_3$	$\sqrt{\frac{2}{2}}k_3$	distorted (derived)

where

$$k_1 = 2 \left[ 2 - \left( \frac{r_2}{r_1} \right)^3 \right]^{\frac{1}{3}}, \text{ and}$$

$$k_3 = \left[ 1 - \frac{1}{2} \left( \frac{r_4}{r_3} \right)^2 \right]^{\frac{1}{2}}.$$

TABLE II

## Detailed Dimensions of Prototype and Model

Dimensions	Prototype		Model
	Stock	Measured	Measured
	Inches (Meters)	Inches (Meters)	Inches (Meters)
L	-----	28.364 (.72042)	14.182 (.3602)
W	-----	15.709 (.3989)	7.854 (.1995)
d	0.1285 (.003264)	0.257 (.006528) <sup>‡</sup>	0.1285 (.003264)
b	0.064 (.001626)	0.065 (.001651)	0.065 (.001651)
h	-----	7.726 (.1962)	3.832 (.09733)
r <sub>1</sub>	5.866 (.1490)	5.880 <sup>†</sup> (.1493)	2.877 (.07307)
r <sub>2</sub>	6.000 (.1524)	-----	3.000 (.07620)
r <sub>3</sub>	1.706 (.04333)	1.707 <sup>†</sup> (.04336)	0.701 (.001780)
r <sub>4</sub>	1.964 (.04988)	-----	0.982 (.02494)

<sup>†</sup> r<sub>2</sub> - r<sub>1</sub> was measured 0.120 inches (.003048 m), r<sub>4</sub> - r<sub>3</sub> was measured 0.257 inches (.006528 m).

<sup>‡</sup> Measured value was 2d

itself would have a very small characteristic time and low heat capacity. The sandwich arrangement was to be used for both the prototype and model. This arrangement would have allowed an approximate scaling of the heaters according to the following reasoning. By the modeling rules, the area of one side of the model plate would be  $\frac{1}{4}$  that of the prototype. Assuming that the same heater material in the same wiring arrangement is used for both the prototype and model, the heat capacity of the heater will be directly proportional to the area of one side of the plate in both. So, the heater heat capacity for the model will be  $\frac{1}{4}$  of that of the prototype. Since the internal generation is also scaled by  $\frac{1}{4}$ , the ratio  $q_1/C_1$  will not be affected by the heater. In all of the ratios  $R_{k1}/C_1$ ,  $C_1$  is scaled by  $\frac{1}{4}$ , since  $d^* = d$ ; there is also a  $\frac{1}{4}$  overall scaling of the numerator, so these ratios would not be affected either. It turned out that the sandwich construction was too difficult, especially with regard to the heater construction and mounting. Therefore, grooves were made in the plates. The wiring was routed through the grooves which were then filled with a special thermally conductive and electrically insulating cement. Roughly speaking, the same reasoning applies as for the intended sandwich construction, except that in making the grooves the plate material was removed before the cement material was added. In this respect, it was to a great extent fortuitous that the detailed modeling criteria presented in Table I was used.

Welding was used to fabricate the cylinder and to mate hemispheres. The amount of material in these welds contributes to the heat capacity. In order to minimize error from this source, all welds were ground to the contour of the external surfaces and care was taken to prevent excessive accumulation of weld material on the inside.

The thickness of thermal coatings could contribute significantly to the heat capacity, especially in the very small models. This problem was solved by smoking the surfaces of both prototype and model with carbon black produced by an acetylene torch. Resulting emittances were 0.98 to 0.99, according to measurements.

Another anticipated difficulty was the crudeness of the volume partition of the objects to be modeled. The finer the partition, the closer the basic equations [1] (and consequently, the modeling ratios) represent the object's thermal properties. On the other hand, as the partition becomes finer, the number of ratios that must be satisfied increases rapidly and the model design becomes more complicated. The crudest possible partition was used here, and it was anticipated that this would cause difficulty in analyzing the experimental data if there were large temperature differences around the object. Since the sphere for the first set of tests was made of stainless steel, it was the object most likely to exhibit this effect.

## EXPERIMENTAL APPARATUS AND PROCEDURES

Both prototypes and models were suspended in the vacuum chamber by long, low-conductivity, small-diameter cables to prevent conductive exchange between the objects and the chamber walls. The rectangular chamber was 1.524 x 1.524 meters in cross-section and 3.658 meters in length. Pressure in the chamber during all experiments was  $10^{-4}$  mm Hg or less. The walls were covered with cryopanel which provided a low temperature inclosure. In addition, both prototype and model occupied the same place in the chamber and were oriented in the same

way to minimize chamber influence on the test objects. The models as they appeared when installed in the chamber are shown in Figure 3.

Two sets of experiments were conducted. In the first set, stainless steel spheres and a plate with heaters installed were used. In the second set, changes were introduced in the sphere to obtain a more uniform temperature; the sphere in which heaters were installed was fabricated from aluminum alloy.

The three test objects had a total of 34 thermocouples for the first set of tests and 25 for the second set. Seven thermocouples were used to monitor the vacuum chamber cryopanel temperatures. The individual thermocouple identification numbers and locations are listed in Table III and Figure 4. On Table III, thermocouple number 1 for the first experiment and number 1 for the second experiment are at the same location on the sphere. This is true for thermocouple numbers 1 through 11, but not for any thereafter. For example, thermocouple number 13 for the first experiment and number 12 for the second are at the same location on the sphere. The locations can be seen by referring to Figure 4 in which the thermocouple numbers refer to the first experiment only. A minimum number of carefully located thermocouples was specified in order to minimize the heat conduction through the wires and still obtain adequate information on the temperature differences on opposite sides of the sphere and the cylinder.

Power loads during the power-on phase of the experiments are listed in Table IV.

TABLE III

Individual Thermocouple Identification Numbers and Locations

Object	Thermocouple Number	
	First Experiment	Second Experiment
Sphere	1	1
	2	2
	3	3
	4	4
	5	5
	6	6
	7	7
	8	8
	9	9
	10	10
	11	11
	12	--
	13	12
	14	13
	15	14
	16	15
Cylinder	17	16
	18	17
	19	--
	20	--
	21	--
	22	--
	23	18
	24	19
Flat Plate	25	20
	26	21
	27	22
	28	23
	29	24
	30	--
	31	--
	32	25
	33	--
	34	--

Note: Thermocouples 1 through 11 are at the same location in both experiments. Thereafter, the numbers vary. For example, thermocouple #13 for the first experiment and thermocouple #12 for the second experiment are in the same location on the sphere, etc.



TABLE IV

Power Loads  
(watts)

Object	Prototype		Model	
	Set 1	Set 2	Set 1	Set 2
Plate	1053	1053	264	264
Sphere	0	400	0	100
Cylinder	0	0	0	0

An important aspect of modeling in the transient case is the initial conditions of the experiments. The temperature distribution for both model and prototype must be the same at the start of the test (or, in general, if temperatures are scaled, then an analogous statement holds for homologous temperatures at zero time). The difficulties arise when considering the duplication of cryopanel cool-down and heater turn-on. In order to eliminate possible differences in individual cryopanel cool-down curves due to different ambient starting temperatures, nitrogen flow rates, and manifolding between panels, the following experiment sequence was specified and used. A vacuum was established, then for both prototype and model, heaters and nitrogen for the panels were activated simultaneously and the systems were allowed to go to practical equilibrium. (If the heaters were not also activated, the objects under experiment would go slowly to panel temperature, taking

much more time and possibly causing difficulty with heaters, paints, and instrumentation at the low temperatures that would be obtained). A detailed analysis of various conditions is given in Ref. [ 3 ] . These equilibrium conditions were considered to be the initial conditions for the experiments. Then, the actual experiment sequence was cooling from these initial conditions (heaters suddenly "off") for two hours, then heating (heaters suddenly "on") for two hours. The periodic nature of these experiments has the inherent advantage of eliminating or minimizing the initial conditions which act as transients in the system, and which are eventually damped out by the thermal inertia of the system.

## RESULTS AND DISCUSSION

Figures 5-16 show the experimental results for the first set of experiments. In all such graphs, temperature is plotted as a function of time and each prototype and corresponding model temperature is plotted on the same graph. The results for all cylinder and plate temperatures are excellent, and the model temperatures would be entirely adequate for predicting prototype temperatures. Two of the temperatures for the sphere (Figures 6 and 8) are acceptable, the differences between prototype and corresponding model temperatures being less than  $8^{\circ}\text{K}$ . However, two of the model temperatures for the sphere (Figures 5 and 7) are not good predictors of the corresponding prototype temperatures. The reason for this is clear. One of them, thermocouple number 3 (Figure 7), is the one nearest the heated plate, and the other, thermocouple number 1 (Figure 5), is the one farthest away from the heated plate. The low conductivity of the stainless steel sphere, together with the asymmetric heating by radiation from the plate, is not

consistent with the crude volume partition of the sphere. In other words, the a priori assumption that the model sphere can be designed using a single representative temperature is too crude. This is shown clearly in Figure 29, in which all sphere temperatures are plotted on one graph. It should be noted that all curves have the proper general shape.

The experimental results for the second set of experiments are shown in Figures 17-28. Here the spheres were constructed of aluminum and had some power dissipation in them (Table IV) in an attempt to obtain more uniform sphere temperatures. The expected improvement was obtained (compare Figures 29 and 30). The model temperatures for the sphere may be used to predict the corresponding prototype temperatures with good results, as can be seen from Figures 17 through 20. The cylinder curves (Figures 21-24) are not as good in this experiment as they were in the first. Again, as can be seen by reference to the geometric arrangement (Figures 1 and 3), the combined heating of the sphere and the plate with asymmetric relative locations makes the assumption of a single representative temperature for the cylinder somewhat questionable (Figures 31-32) although not nearly as much so as for the sphere. In addition, and perhaps more importantly, the initial conditions for the prototype and model were not properly established; this is shown clearly by the graphs. Furthermore, the results for the plate (Figures 25-28) are not nearly as good in the second experiment as in the first. This is surprising since both sets of experiments used the same prototype and model plates. Furthermore, the reason for these apparently anomalous results for plate cannot be due to the fact that the sphere was heated in one experiment and not in the other since all temperatures over the plate show this same effect. The heating

portion of the curves could be explained by overheating of the models, but this would not explain the cooling portion of the curves. However, both heating and cooling curves can be explained by a lower emissivity for the model than the prototype. Coatings for these were smoked-on carbon black, which handling removes easily, and it is plausible that some of the carbon black was inadvertently removed from the model plate. The results for the second set of experiments are also shown in Tables V, VI, and VII. They are self-explanatory.

### CONCLUSIONS

1. The modeling laws are generally confirmed by the experiment.
2. The volume partitioning used here was too crude; the sphere should have been divided into at least four regions.
3. Electrical resistance heaters are very useful to simulate internal energy dissipation but are not entirely satisfactory to simulate incident radiation because they necessarily become a part of the objects to be modeled, requiring that they also must be modeled.
4. Considerable care must be used in obtaining proper initial conditions if model experiments are to be used to predict prototype temperatures in transient cases that are not periodic.

TABLE V

SUMMARY OF THERMOCOUPLE READINGS FOR SECOND SET OF EXPERIMENTS. TEMPERATURES IN DEGREES KELVIN.

(FOR EACH TIME PROTOTYPE READING IS LISTED FIRST, MODEL READING NEXT AND DIFFERENCE BETWEEN THEM LAST)

THERMOCOUPLE NUMBER

TIME (MIN)	THERMOCOUPLE NUMBER																								
	SPHERE															CYLINDER					FLAT PLATE				
	1	2	3	4	5	6	7	8	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
0	301	301	301	301	301	301	301	301	301	301	301	301	301	301	301	301	301	301	301	300	301	300	301	301	
0	289	289	289	289	289	289	289	289	289	289	289	289	289	289	288	288	288	288	297	296	297	297	297	296	
DIF	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-13	-13	-13	-13	-4	-3	-5	-3	-4	-5	
10	338	344	339	337	337	340	338	336	338	338	341	343	336	334	301	301	300	300	351	351	344	346	354	353	
10	307	308	317	309	324	322	313	309	328	332	333	394	333	310	289	293	289	289	373	374	372	374	374	375	
DIF	-31	-36	-22	-28	-13	-18	-25	-27	-10	-6	-8	51	-3	-24	-12	-11	-11	-11	22	23	28	28	20	22	
20	368	377	378	370	366	372	376	367	372	374	371	374	372	382	302	301	298	298	417	418	409	406	424	421	
20	352	354	357	355	382	372	361	358	383	386	332	472	390	357	292	294	293	292	422	422	419	423	423	424	
DIF	-16	-23	-11	-15	16	0	-15	-9	11	12	-39	98	18	-25	-10	-7	-5	-6	5	4	10	17	-1	3	
30	397	407	411	401	394	403	408	397	403	406	400	403	404	414	303	301	297	298	441	445	434	422	451	447	
30	392	394	428	395	418	410	402	398	424	423	346	504	428	397	297	299	298	298	442	442	439	444	444	445	
DIF	-5	-13	-3	-6	24	7	-6	1	21	14	-54	101	24	-17	-6	-2	1	0	1	-3	5	22	-7	-2	
40	416	425	431	420	413	422	428	416	422	425	419	422	423	434	304	302	297	298	448	453	441	429	458	455	
40	415	417	432	418	438	433	425	421	435	439	346	519	453	419	302	306	304	303	450	451	448	453	454	454	
DIF	-1	-8	1	-2	25	11	-3	5	13	14	-73	97	30	-15	-2	4	7	5	2	-2	7	24	-4	-1	
50	427	436	442	431	424	432	438	426	432	436	430	432	434	446	305	303	298	298	449	456	442	432	461	457	
50	427	428	443	430	448	443	381	433	442	449	332	526	465	431	308	311	309	308	453	454	452	457	457	458	
DIF	0	-8	1	-1	24	11	-57	7	10	13	-98	94	31	-15	3	8	11	10	4	-2	10	25	-4	1	
60	433	441	447	436	431	437	443	431	436	441	436	436	439	451	306	304	298	299	449	456	442	434	461	457	
60	432	434	449	436	452	448	442	439	446	454	332	529	443	435	313	316	314	313	456	453	453	459	459	459	
DIF	-1	-7	2	0	21	11	-1	8	10	13	-104	93	4	-15	7	12	16	14	7	-3	11	25	-2	2	
70	448	457	459	449	446	451	455	443	448	454	451	449	451	464	307	306	299	300	449	457	442	436	462	458	
70	443	445	462	447	464	460	453	451	458	467	330	548	489	447	317	320	318	318	454	454	453	458	458	459	
DIF	-5	-12	3	-2	18	9	-2	8	10	13	-121	99	38	-17	10	14	19	18	5	-3	11	22	-4	1	

TABLE V (CONT.)

	SPHERE															CYLINDER					FLAT PLATE				
	1	2	3	4	5	6	7	8	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
80	459	469	469	461	458	462	465	454	458	464	462	460	461	475	309	308	301	302	449	458	443	437	463	459	
80	451	453	469	454	471	468	461	459	463	473	346	553	497	469	320	323	322	321	453	453	452	458	458	458	
DIF	-8	-16	0	-7	13	6	-4	5	5	9	-116	93	36	-6	11	15	21	19	4	-5	9	21	-5	-1	
90	466	474	474	466	464	467	470	459	463	470	467	465	467	481	311	310	303	303	449	459	443	438	463	459	
90	454	456	472	457	472	471	463	462	466	475	346	554	498	457	323	326	324	324	453	453	452	458	458	458	
DIF	-12	-18	-2	-9	8	4	-7	3	3	5	-121	89	31	-24	12	16	21	21	4	-6	9	20	-5	-1	
100	468	477	477	469	467	469	472	462	464	472	469	467	469	483	313	312	304	305	449	459	442	438	463	459	
100	456	473	458	472	471	464	463	463	466	476	331	555	499	458	325	328	327	326	452	453	452	458	458	458	
DIF	-19	-21	-4	-11	5	2	-8	1	2	4	-138	88	30	-25	12	16	23	21	3	-6	10	20	-5	-1	
110	468	477	478	470	468	469	473	463	465	473	470	467	469	484	314	313	306	307	449	458	442	438	463	459	
110	455	457	473	458	472	471	464	463	466	476	347	555	499	458	326	329	328	327	453	453	452	458	458	458	
DIF	-19	-20	-5	-12	4	2	-9	0	1	3	-123	88	30	-26	12	16	22	20	4	-5	10	20	-5	-1	
120	468	477	478	471	468	469	473	463	465	473	470	467	469	484	316	314	307	308	448	458	441	437	461	457	
120	455	457	473	458	472	471	464	463	466	476	347	556	498	458	327	330	329	328	452	452	452	457	458	457	
DIF	-19	-20	-5	-13	4	2	-9	0	1	3	-123	89	29	-26	11	16	22	20	4	-6	11	20	-3	3	
HEATER OFF																									
130	422	429	431	427	422	423	428	422	422	427	422	424	426	435	311	311	305	306	367	376	362	367	377	374	
130	411	412	418	413	417	419	415	415	418	420	340	456	431	412	323	325	324	324	388	388	389	393	393	392	
DIF	-11	-17	-13	-14	-5	-4	-13	-7	-4	-7	-82	32	5	-23	12	14	19	18	21	12	27	26	16	18	
140	381	386	388	384	381	381	384	381	381	384	381	382	383	394	302	302	297	298	323	332	319	325	331	329	
140	370	371	376	372	375	376	373	372	377	378	337	404	383	371	314	316	315	315	349	349	349	352	352	352	
DIF	-11	-15	-12	-12	-6	-5	-11	-9	-4	-6	-44	22	0	-23	12	14	18	17	26	17	30	27	21	23	
150	352	355	356	354	351	352	354	351	351	353	352	352	353	364	293	293	289	289	296	303	293	298	302	301	
150	342	342	346	343	345	346	344	343	347	348	341	370	351	342	304	305	305	304	323	323	323	326	326	325	
DIF	-10	-13	-13	-11	-6	-6	-10	-8	-4	-5	-11	18	-2	-22	11	12	16	15	27	20	30	28	24	24	
160	324	326	328	325	323	323	326	323	323	325	324	324	324	334	282	282	278	278	272	278	269	274	277	276	
160	320	321	323	321	323	324	322	321	325	326	361	344	328	321	294	295	294	295	304	304	304	306	306	306	
DIF	-4	-5	-5	-4	2	1	-4	-2	2	1	17	20	4	-13	12	13	16	17	32	26	35	32	29	30	
170	309	311	312	309	308	308	310	308	308	308	308	309	308	318	275	275	270	271	259	264	256	262	263	262	
170	303	304	306	304	306	307	305	304	307	308	319	325	310	304	285	286	286	286	289	289	289	291	291	290	
DIF	-6	-7	-6	-5	-2	-1	-5	-4	-1	-1	11	16	1	-14	10	11	16	15	30	25	33	29	28	28	
180	293	296	297	294	293	293	294	293	293	294	293	294	294	294	267	267	262	263	247	251	244	249	251	249	
180	290	291	292	291	292	293	292	291	294	295	341	310	296	291	277	277	277	277	277	277	277	278	278	278	
DIF	-3	-5	-5	-3	-1	0	-2	-2	1	1	48	16	2	-11	10	10	15	14	30	26	33	29	27	29	

18

SPHERE										CYLINDER										FLAT PLATE				
1	2	3	4	5	6	7	8	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
190	281	283	283	282	281	281	282	281	281	281	281	282	281	288	259	263	254	256	236	240	234	238	239	238
190	278	278	282	278	281	279	278	281	282	282	282	283	278	268	269	269	269	266	266	266	267	267	267	
DIF	-3	-5	-3	-4	-2	0	-3	0	1	59	14	2	-10	9	9	15	13	30	26	32	29	28	29	
200	270	272	273	271	275	270	271	270	270	270	270	271	271	278	253	253	248	249	228	231	225	229	231	229
200	272	272	273	272	273	274	273	272	274	276	341	288	277	272	264	264	264	264	261	261	261	262	262	261
DIF	2	0	0	1	3	4	2	2	4	6	71	17	6	-6	11	11	16	15	33	30	36	33	31	32
210	261	262	263	261	261	261	261	261	261	261	261	261	261	268	246	247	241	243	219	223	218	221	222	222
210	262	262	263	262	263	264	263	262	264	266	341	277	266	262	256	257	257	257	252	252	252	252	252	252
DIF	1	0	0	1	2	3	2	1	3	5	80	16	5	-5	10	10	16	14	33	29	34	31	30	33
220	253	254	255	253	253	253	254	253	253	253	253	253	253	260	241	241	236	238	214	216	212	215	216	215
220	256	256	257	256	257	257	256	256	258	259	341	289	259	256	251	251	246	246	246	246	246	246	246	246
DIF	3	2	2	3	4	4	2	3	5	6	88	16	6	-4	10	11	15	13	32	30	34	31	30	31
230	245	247	247	246	245	245	246	245	245	245	246	246	246	252	235	236	230	232	208	238	206	209	209	209
230	249	249	250	249	250	251	250	249	251	252	341	262	253	249	246	246	246	246	240	240	240	241	241	241
DIF	4	2	3	3	5	6	4	4	6	7	95	16	7	-3	11	10	16	14	32	2	34	32	32	32
240	239	241	241	239	239	239	271	239	239	239	239	242	239	245	231	231	224	227	203	205	201	204	204	204
240	244	244	246	244	245	246	245	244	246	247	341	256	248	244	242	242	242	242	236	236	236	236	236	236
DIF	5	3	5	5	5	7	-26	5	7	8	102	16	9	-2	11	11	16	15	33	31	35	32	32	32
HEATER BN																								
250	264	271	268	266	263	258	258	257	257	259	265	269	257	293	228	228	222	223	316	317	309	313	319	317
250	282	283	287	284	315	304	290	286	320	328	332	439	332	285	239	243	239	239	337	338	336	338	338	339
DIF	18	12	29	18	50	46	32	29	63	69	67	170	75	-8	11	12	17	16	21	21	27	25	19	22
260	326	308	332	323	321	319	319	315	316	321	328	333	317	352	229	229	222	223	392	395	386	379	399	397
260	349	351	357	352	385	372	359	358	391	389	332	504	402	353	242	244	243	242	396	397	394	398	398	399
DIF	23	43	35	29	65	53	40	43	75	68	4	174	85	1	13	15	21	19	4	2	8	19	-1	2
270	382	387	387	376	376	378	381	371	373	379	382	384	374	404	235	234	226	227	422	426	416	408	431	428
270	402	403	421	402	434	422	407	469	439	432	346	529	449	406	256	254	252	251	426	426	424	429	429	429
DIF	20	16	34	29	58	44	86	98	66	53	-36	145	75	2	21	23	26	24	4	0	8	21	-2	1
280	422	432	429	418	417	420	422	413	415	422	422	423	418	443	244	243	235	236	436	442	429	424	447	444
280	452	434	452	436	456	453	442	443	447	458	332	544	483	436	284	267	266	266	441	441	439	445	445	445
DIF	10	2	23	18	39	30	20	30	32	36	-90	121	65	-7	23	24	31	28	5	-1	10	21	-2	1
290	441	458	453	440	438	441	444	434	436	444	442	443	440	462	255	253	244	246	441	449	434	431	453	450
290	444	464	464	448	464	462	454	454	456	468	346	551	492	448	275	279	277	276	446	446	445	451	451	451
DIF	3	-12	14	8	26	21	10	20	23	24	-96	108	52	-14	20	26	33	30	5	-2	11	20	-2	1

TABLE V (CONT.)

	SPHERE										CYLINDER					FLAT PLATE								
	1	2	3	4	5	6	7	8	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
300	451	471	461	452	448	451	454	445	447	454	452	453	451	471	266	264	255	256	444	452	437	434	457	453
300	451	452	470	454	459	467	460	461	461	473	332	334	336	454	287	290	288	288	449	449	448	454	454	454
DIF	0	-19	9	2	21	16	6	16	14	19	-120	101	45	-17	21	26	33	32	5	-3	11	20	-3	1
310	455	476	465	457	453	456	459	450	451	459	456	457	456	474	274	273	264	266	444	454	438	436	458	454
310	453	455	473	457	471	470	463	463	464	476	346	346	346	458	296	299	298	297	451	451	449	456	456	456
DIF	-2	-21	8	0	18	14	4	13	13	17	-110	99	42	-17	22	26	34	31	7	-3	11	20	-2	2
320	457	478	467	459	456	457	462	452	453	461	458	459	458	476	283	282	273	273	444	454	438	436	458	454
320	454	456	474	458	472	471	464	464	464	477	346	346	346	458	303	307	305	304	451	451	450	456	456	456
DIF	-3	-22	7	-1	16	14	2	12	11	16	-112	97	40	-18	20	25	32	31	7	-3	12	20	-2	2
330	458	478	468	460	456	458	462	453	454	462	459	459	459	477	289	288	279	280	444	454	438	436	458	454
330	455	457	474	459	472	472	464	465	465	477	332	332	332	458	309	313	311	310	451	451	450	456	456	456
DIF	-3	-21	6	-1	16	14	2	12	11	15	-127	98	40	-19	20	25	32	30	7	-3	12	20	-2	2
340	458	479	468	460	457	458	458	453	454	462	459	459	459	477	295	294	286	286	444	454	438	436	457	454
340	456	457	475	459	472	472	465	466	465	477	346	346	346	458	314	317	316	315	452	452	451	457	457	457
DIF	-2	-22	7	-1	15	14	209	13	11	15	-113	98	40	-18	19	23	30	29	8	-2	13	21	0	3
350	458	479	468	461	457	459	463	454	454	462	459	462	459	477	299	299	291	291	444	454	438	436	457	454
350	456	458	475	459	482	472	466	466	466	478	332	332	332	459	317	321	319	318	452	452	451	457	457	457
DIF	-2	-21	7	-2	15	13	3	12	12	16	-127	97	40	-18	18	22	28	27	8	-2	13	21	0	3
360	459	479	468	461	457	459	463	454	455	463	459	460	460	478	303	302	294	295	444	454	438	437	458	454
360	456	458	476	460	472	472	466	466	466	478	346	346	346	458	319	323	322	321	452	452	452	457	458	457
DIF	-3	-21	8	-1	15	13	3	12	11	15	-113	98	39	-19	16	21	28	26	8	-2	14	20	0	3
HEATER OFF																								
370	417	431	427	421	417	418	422	417	417	422	417	418	422	433	301	301	294	295	367	376	363	367	374	374
370	411	411	418	413	417	419	415	416	417	420	340	340	340	456	317	319	318	318	388	388	389	392	392	391
DIF	-6	-20	-9	-8	0	1	-7	-1	0	-2	-77	38	9	-22	16	18	24	23	21	12	26	25	16	17
380	368	374	374	370	367	367	371	367	367	370	367	368	369	383	292	292	287	288	313	321	310	315	320	318
380	369	370	375	371	374	376	373	372	377	378	340	340	340	453	309	311	311	310	348	348	349	351	351	351
DIF	1	-4	1	1	7	9	2	5	10	8	-27	35	15	-13	17	19	24	22	35	27	39	36	31	33
390	347	352	349	346	347	349	346	346	346	348	347	347	347	348	286	286	282	282	294	301	291	296	300	298
390	341	341	344	342	344	345	343	343	346	347	341	349	352	361	300	301	301	301	322	322	322	324	324	324
DIF	-6	-11	-8	-7	-2	-2	-6	-3	0	-1	-6	22	4	-23	15	15	19	19	28	21	31	28	24	26
400	324	327	327	324	322	323	324	323	322	324	323	323	324	334	278	278	273	274	273	279	271	276	278	277
400	319	319	322	320	321	323	321	321	324	324	341	343	329	319	291	292	291	291	303	303	303	304	304	304
DIF	-5	-8	-5	-4	-1	0	-3	-2	2	0	18	20	5	-15	13	14	18	17	30	24	32	28	26	27



TABLE V (CONT.)

	SPHERE															CYLINDER					FLAT PLATE				
	1	2	3	4	5	6	7	8	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
410	308	311	311	309	307	308	309	307	307	308	308	308	308	317	271	271	267	268	260	266	258	263	264	263	
419	302	322	325	323	304	326	304	324	324	307	308	341	324	311	303	282	283	282	288	288	288	289	289	289	
DIF	-6	-9	-6	-6	-3	-2	-5	-3	0	0	33	16	3	-14	11	12	16	14	28	22	30	26	25	26	
420	294	297	297	295	294	294	296	294	294	294	294	295	294	294	303	264	265	260	261	249	254	247	252	253	
420	289	289	291	289	291	292	290	290	292	293	340	308	296	289	274	274	274	274	276	276	276	277	277	277	
DIF	-5	-8	-6	-6	-3	-2	-6	-4	-2	-1	46	13	2	-14	12	9	14	13	27	22	29	25	24	25	
430	283	285	285	283	282	283	283	282	282	283	283	283	283	290	258	258	254	255	240	244	238	242	243	242	
430	278	278	280	278	279	281	279	279	281	282	340	296	284	278	267	268	268	267	266	266	266	267	267	267	
DIF	-5	-7	-5	-5	-3	-2	-4	-3	-1	-1	57	13	1	-12	9	10	14	12	26	22	28	25	24	25	
440	273	275	275	273	273	273	273	273	273	273	273	273	273	280	253	253	248	249	232	236	231	234	235	234	
440	269	269	271	269	270	271	270	269	272	273	339	285	275	269	261	261	261	261	258	258	258	259	258	258	
DIF	-4	-6	-4	-4	-3	-2	-4	-4	-1	0	66	12	2	-11	8	8	13	12	26	22	27	25	23	24	
450	271	271	269	268	268	268	269	268	268	269	269	269	269	275	250	250	246	247	229	232	228	231	232	231	
450	261	262	263	262	262	263	262	262	264	265	339	276	267	262	255	256	256	255	251	251	251	252	252	251	
DIF	-10	-9	-6	-6	-6	-5	-7	-6	-4	-4	70	7	-1	-14	5	6	10	8	22	19	23	21	20	20	
460	257	258	258	257	256	256	257	256	256	256	256	257	256	263	242	242	238	239	219	222	218	221	222	221	
460	257	255	256	255	256	257	256	256	257	258	339	268	259	255	250	251	250	250	245	245	245	246	246	246	
DIF	0	-3	-2	-2	0	1	-1	0	1	2	83	11	3	-8	8	9	12	11	26	23	27	25	24	25	
470	250	252	251	250	249	250	251	249	250	250	250	251	250	257	237	237	238	233	215	217	214	216	217	216	
470	249	249	251	249	250	251	250	250	251	252	339	262	253	243	245	246	246	246	240	240	240	241	241	242	
DIF	-1	-3	0	-1	1	1	-1	1	1	2	89	11	3	-8	8	8	13	12	25	23	26	25	24	24	
480	244	245	245	244	243	244	244	243	243	243	244	244	244	243	233	233	229	229	210	213	209	211	212	212	
480	244	245	246	245	246	246	246	245	247	248	340	256	249	244	242	242	242	242	236	236	236	236	236	236	
DIF	0	0	1	1	3	2	2	2	4	5	96	12	6	-5	9	9	13	13	26	23	27	25	24	24	

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TABLE VI

Fraction of Time in Percent where the Difference Between the Prototype and Model Temperatures of the Individual Thermocouple Measurements are Equal to or Less than 5, 10, 15, 20, and 25 Degrees Kelvin.<sup>†</sup>

Thermocouple Number	5	10	15	20	25
1	59.2	75.5	89.8	95.9	98.0
2	26.5	46.9	63.3	79.6	95.9
3	51.0	79.6	89.8	89.8	93.9
4	55.1	73.5	89.8	93.9	93.9
5	44.9	57.1	69.4	79.6	89.8
6	51.0	65.3	85.7	89.8	91.8
7	51.0	75.5	83.7	85.7	87.8
8	55.1	71.4	85.7	89.8	89.8
10	53.1	67.3	87.8	89.8	91.8
11	42.9	61.2	81.6	89.8	91.8
12	2.0	6.1	10.2	14.3	14.3
13	0.0	2.0	18.4	40.8	44.9
14	38.8	51.0	55.1	57.1	59.2
15	10.2	28.6	59.2	79.6	95.9
16	6.1	36.7	75.5	93.9	100.0
17	4.1	30.6	67.3	81.6	93.9
18	4.1	8.2	32.7	63.3	79.6
19	4.1	10.2	49.0	71.4	81.6
20	32.7	46.9	46.9	46.9	59.2
21	42.9	49.0	53.1	59.2	83.7
22	4.1	24.5	46.9	46.9	49.0
23	2.0	2.0	2.0	26.5	65.3
24	44.9	46.9	46.9	57.1	77.6
25	46.9	46.9	46.9	53.1	73.5

<sup>†</sup> Determined from discrete points in time corresponding to data readout times.

TABLE VII  
NUMBER OF DIFFERENCES LESS THAN OR EQUAL TO  
5, 10, 15, 20, and 25 DEGREES KELVIN AT VARI-  
OUS TIMES

TIME-MIN	5	10	15	20	25
0	6	6	23	23	23
10	1	4	9	11	17
20	6	11	16	20	22
30	10	15	17	18	22
40	12	15	19	19	21
50	8	14	18	18	20
60	8	13	19	20	22
70	8	12	16	20	21
80	8	14	17	19	21
90	8	13	15	18	21
100	9	12	15	17	21
110	10	12	15	19	20
120	9	11	15	19	20
130	4	6	13	18	20
140	3	6	13	16	20
150	3	9	15	18	21
160	11	11	14	18	18
170	8	12	16	18	19
180	11	13	16	17	17
190	11	14	17	17	17
200	9	12	15	17	17
210	11	14	15	17	17
220	10	13	16	17	17
230	9	14	16	18	18
240	6	11	14	16	16
250	0	1	4	9	13
260	6	7	9	11	13
270	5	6	6	9	12
280	5	8	8	11	14
290	5	7	11	15	17
300	6	8	10	16	18
310	6	8	12	16	18
320	6	8	12	17	19
330	6	8	13	17	19
340	5	7	13	15	18
350	6	8	13	16	19
360	6	8	14	17	19
370	5	10	11	16	21
380	6	10	12	14	16
390	6	11	14	17	20
400	10	11	14	18	19
410	7	11	15	17	19
420	7	13	17	17	21
430	10	13	17	17	21
440	10	13	17	17	21
450	5	16	17	20	23
460	11	14	17	17	21
470	11	14	17	17	22
480	10	14	17	17	21

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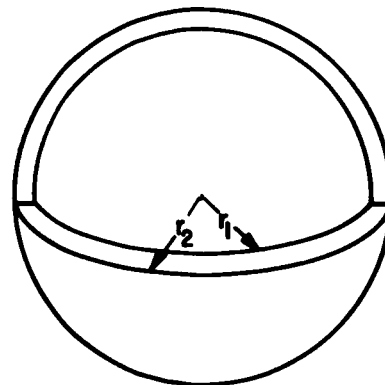
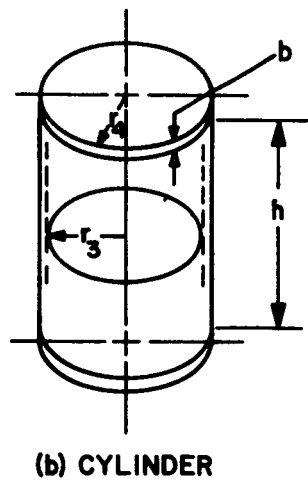
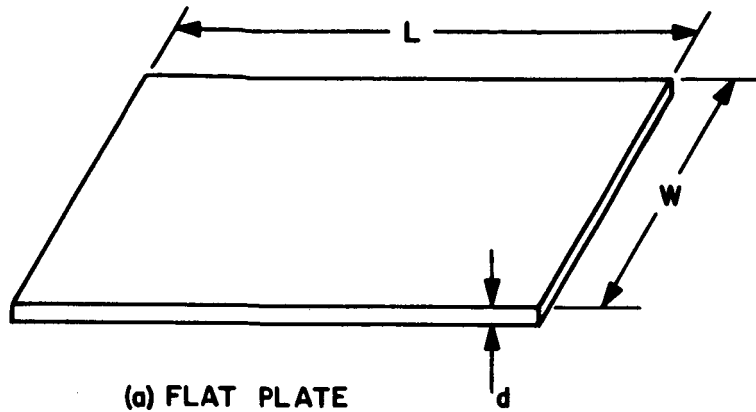


Figure 2 - Dimensional Notation-Numerical Values Given in Table II



Figure 3 - Model Installed in Vacuum Chamber

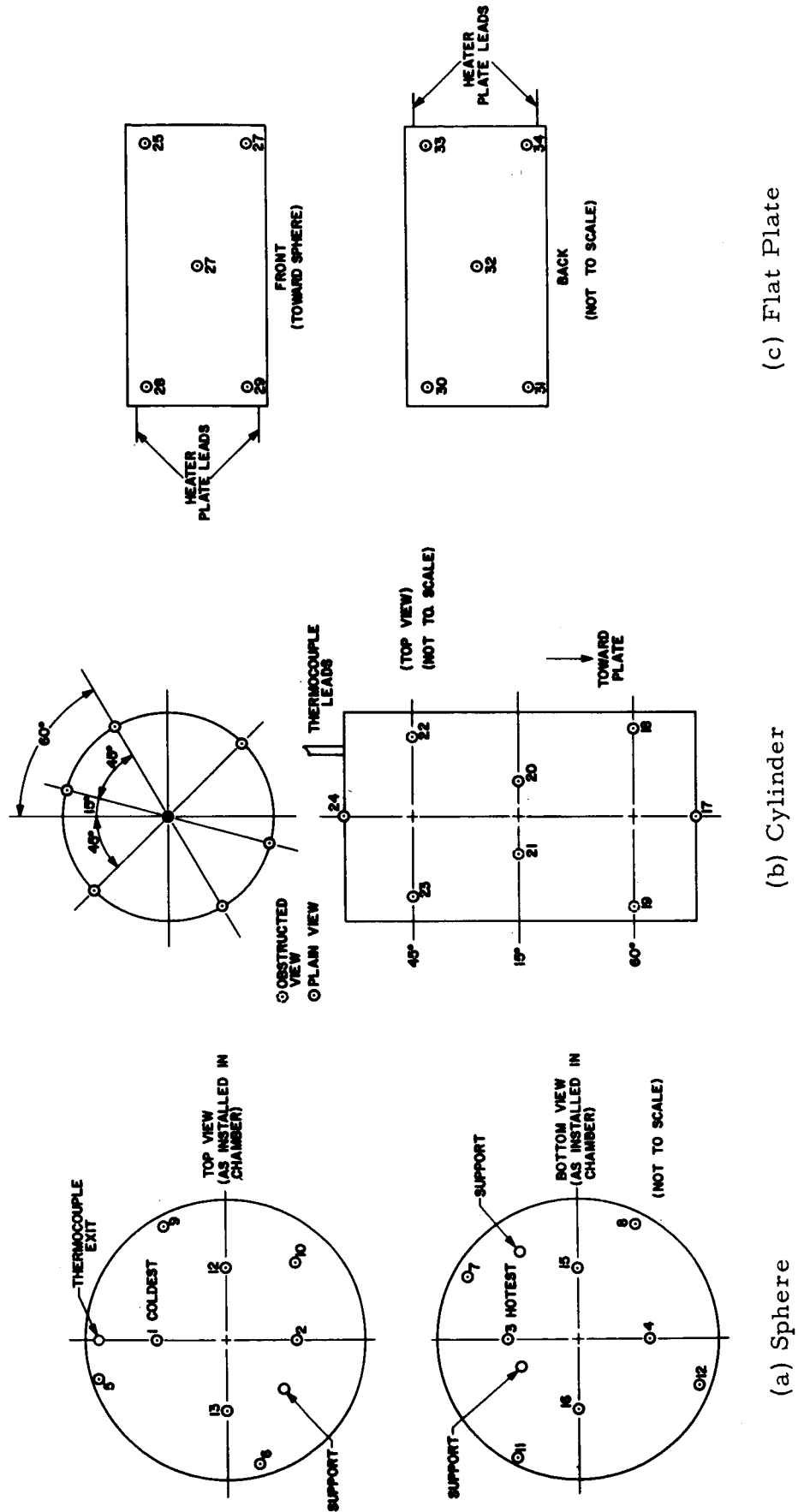


Figure 4 - Individual Thermocouple Identification Numbers and Locations  
(First Experiment only).



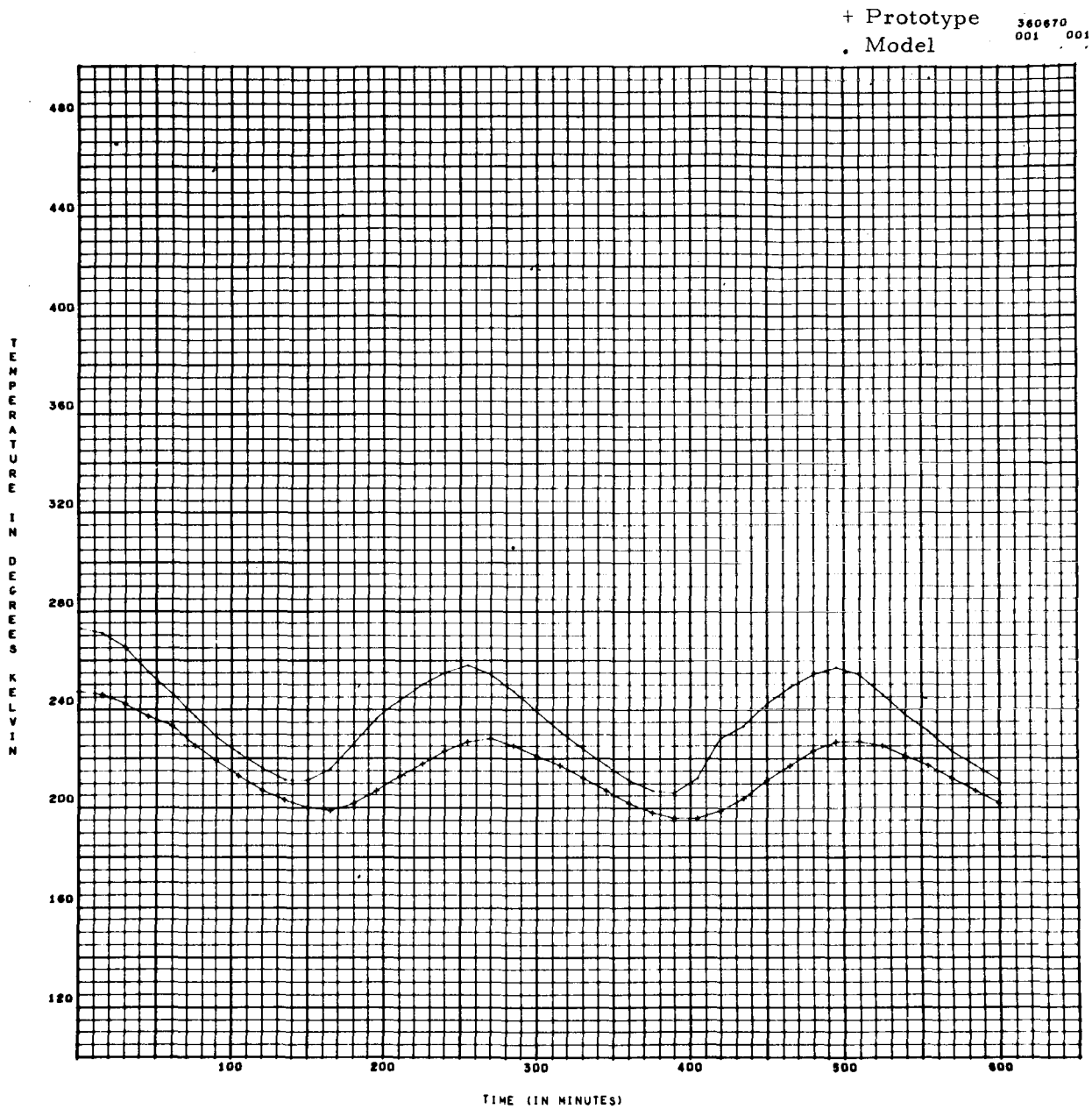


Figure 5 - Temperature-Time, Prototype and Model Sphere, Thermocouple No. 1 (First Experiment)

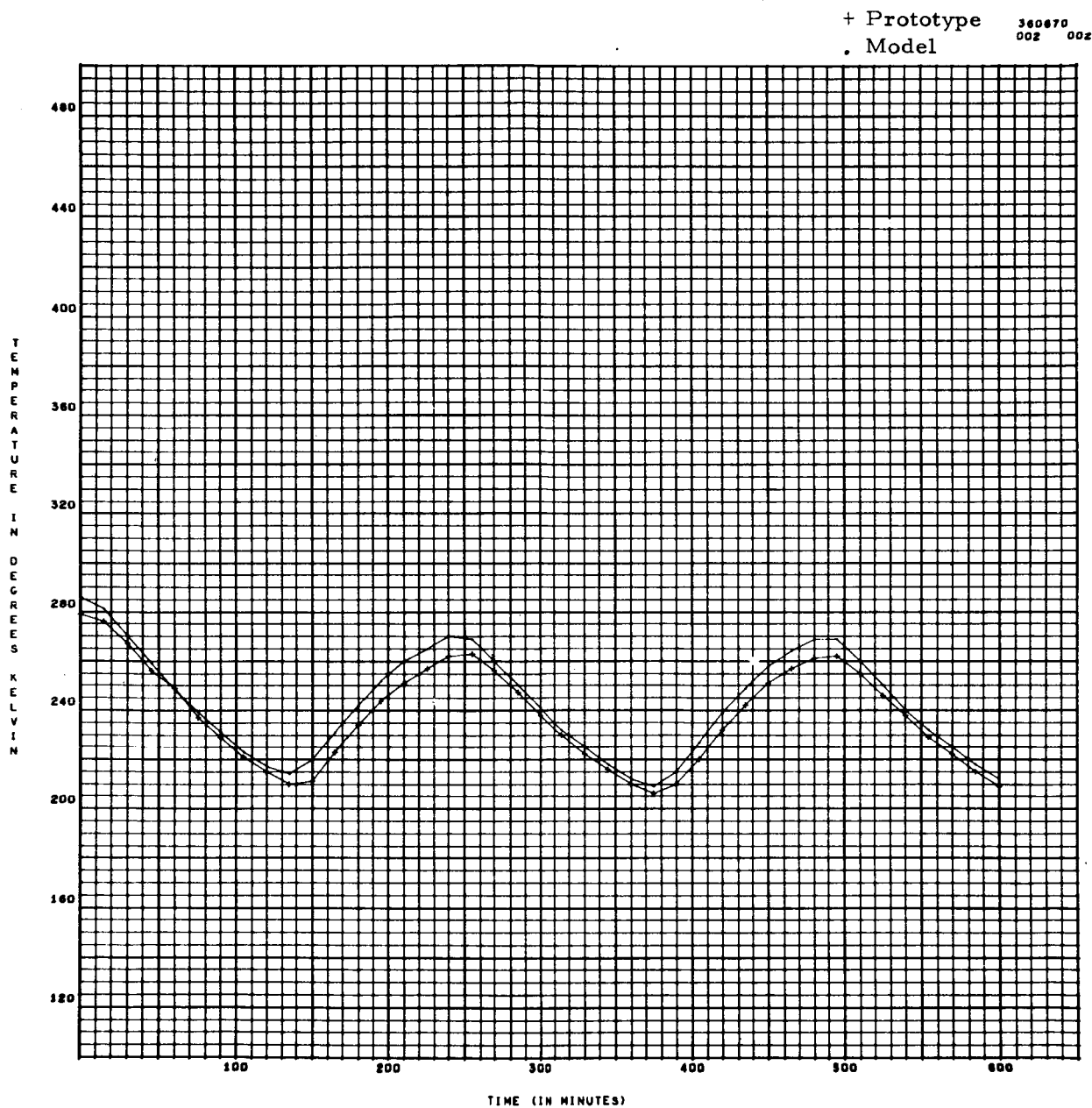


Figure 6 - Temperature-Time, Prototype and Model Sphere, Thermocouple No. 2 (First Experiment)

+ Prototype  
• Model

380870  
003 003

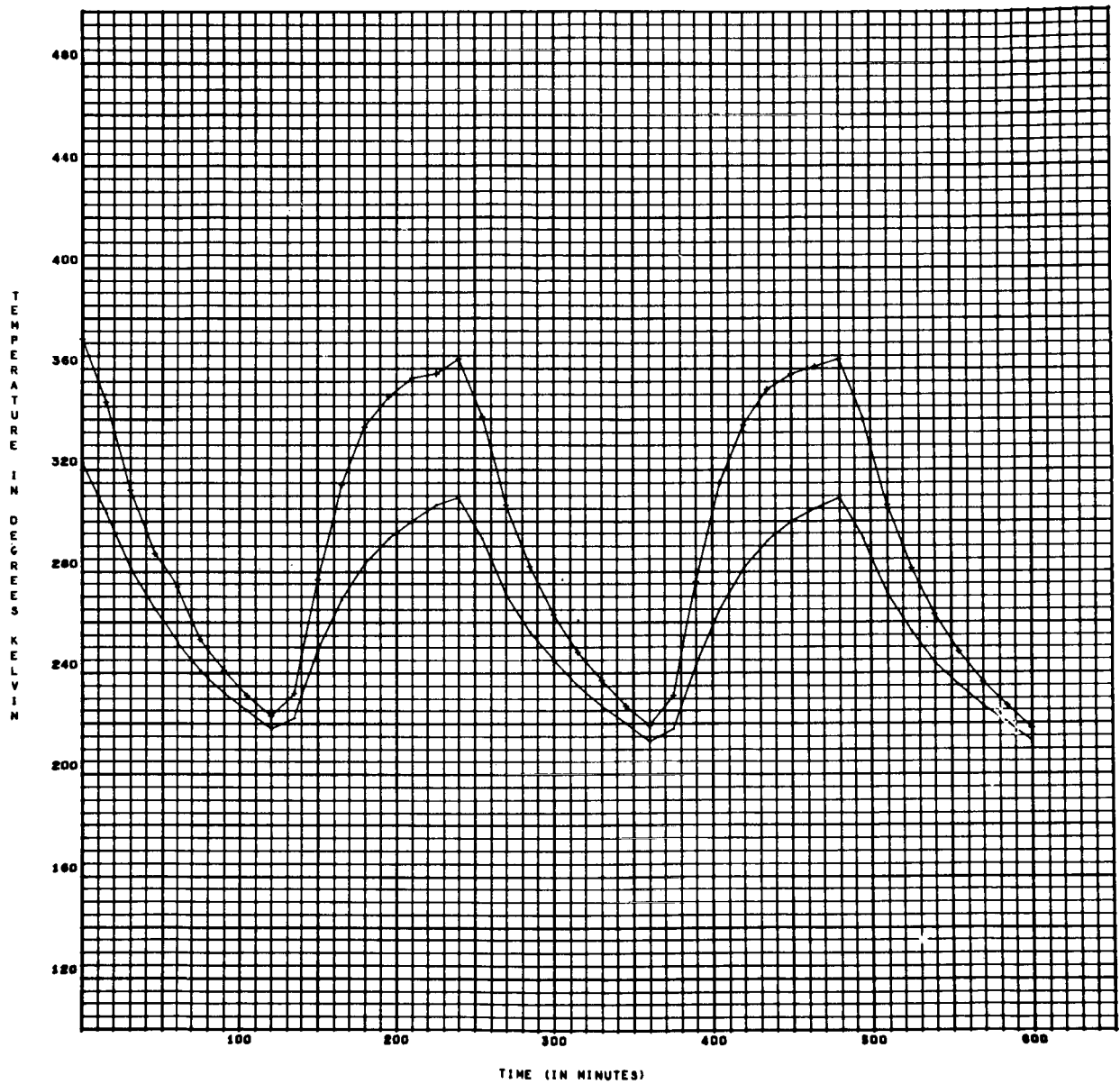


Figure 7 - Temperature-Time, Prototype and Model Sphere, Thermocouple No. 3 (First Experiment)

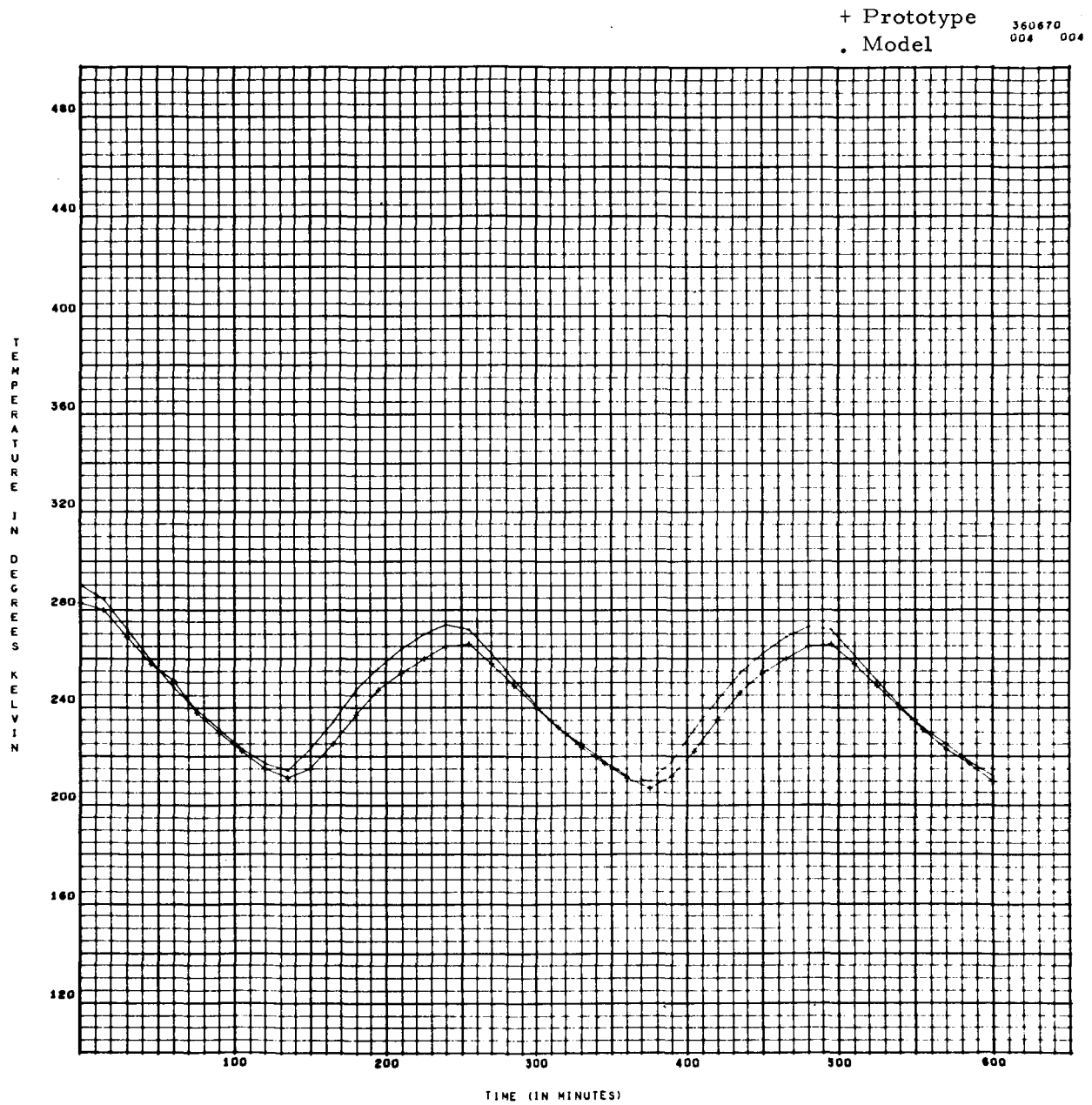


Figure 8 - Temperature-Time, Prototype and Model Sphere, Thermocouple No. 4 (First Experiment)

+ Prototype  
• Model

380670  
005 005

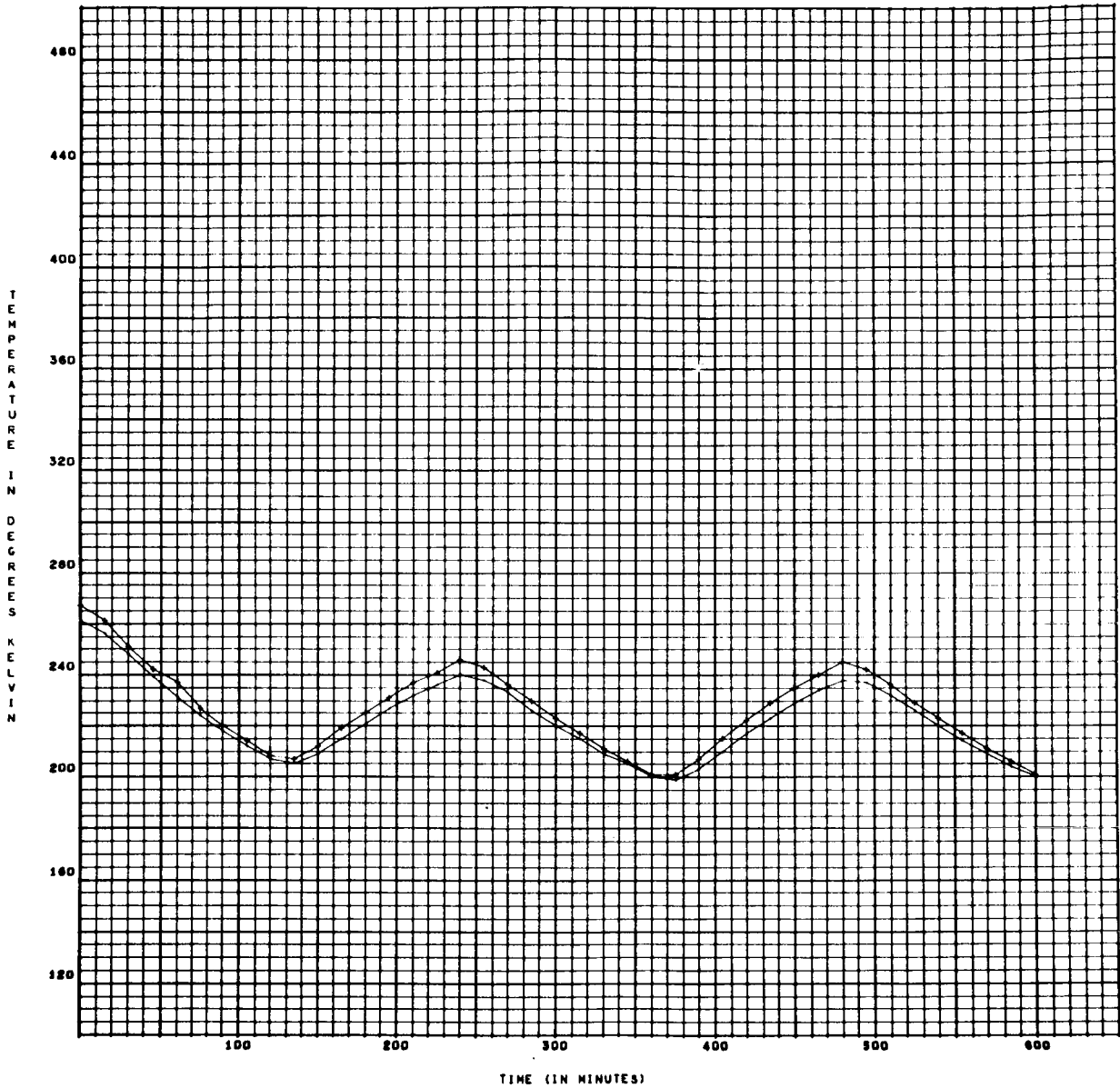


Figure 9 - Temperature-Time, Prototype and Model Cylinder, Thermocouple No. 17 (First Experiment)

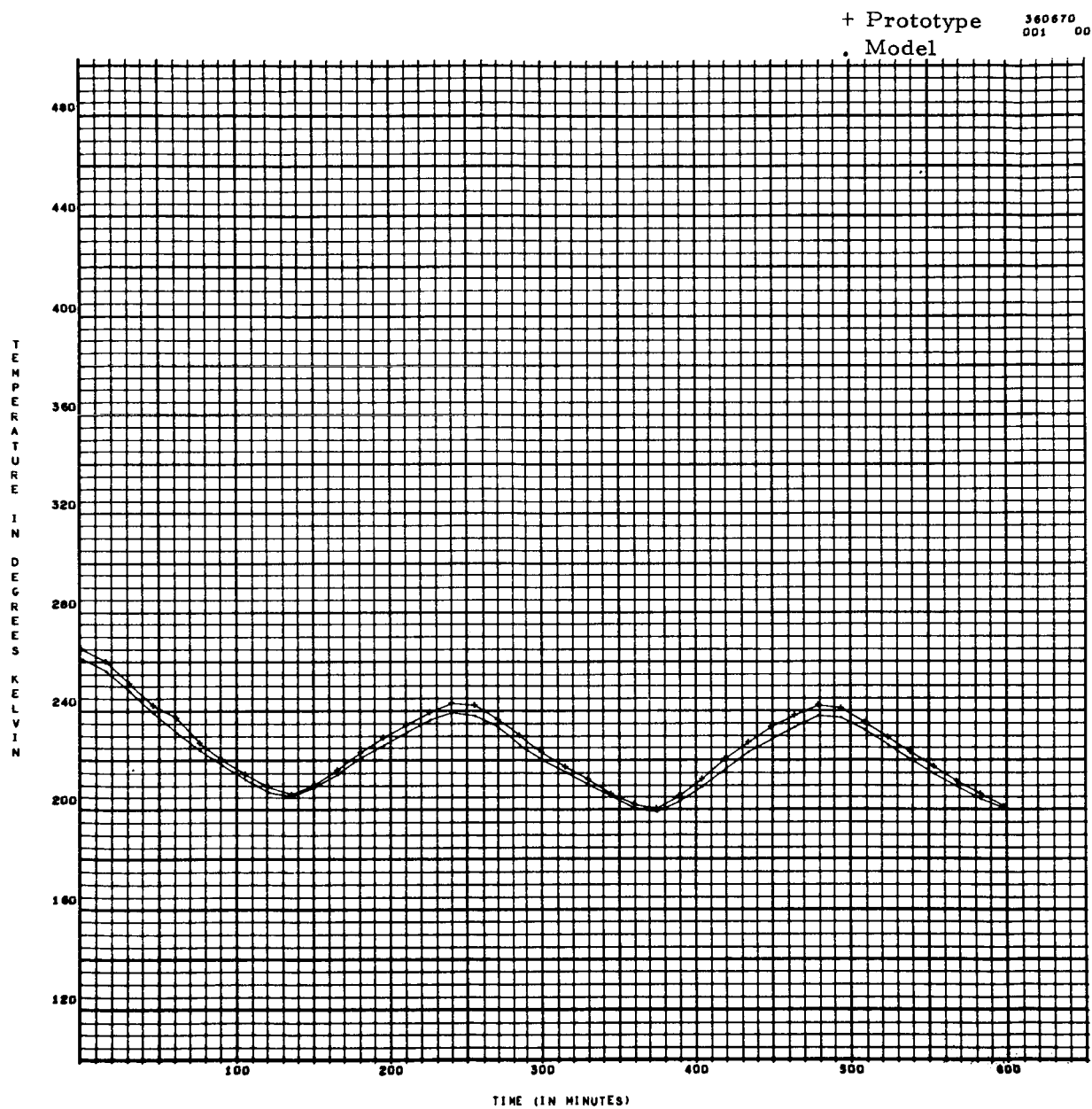


Figure 10 - Temperature-Time, Prototype and Model Cylinder, Thermocouple No. 19 (First Experiment)

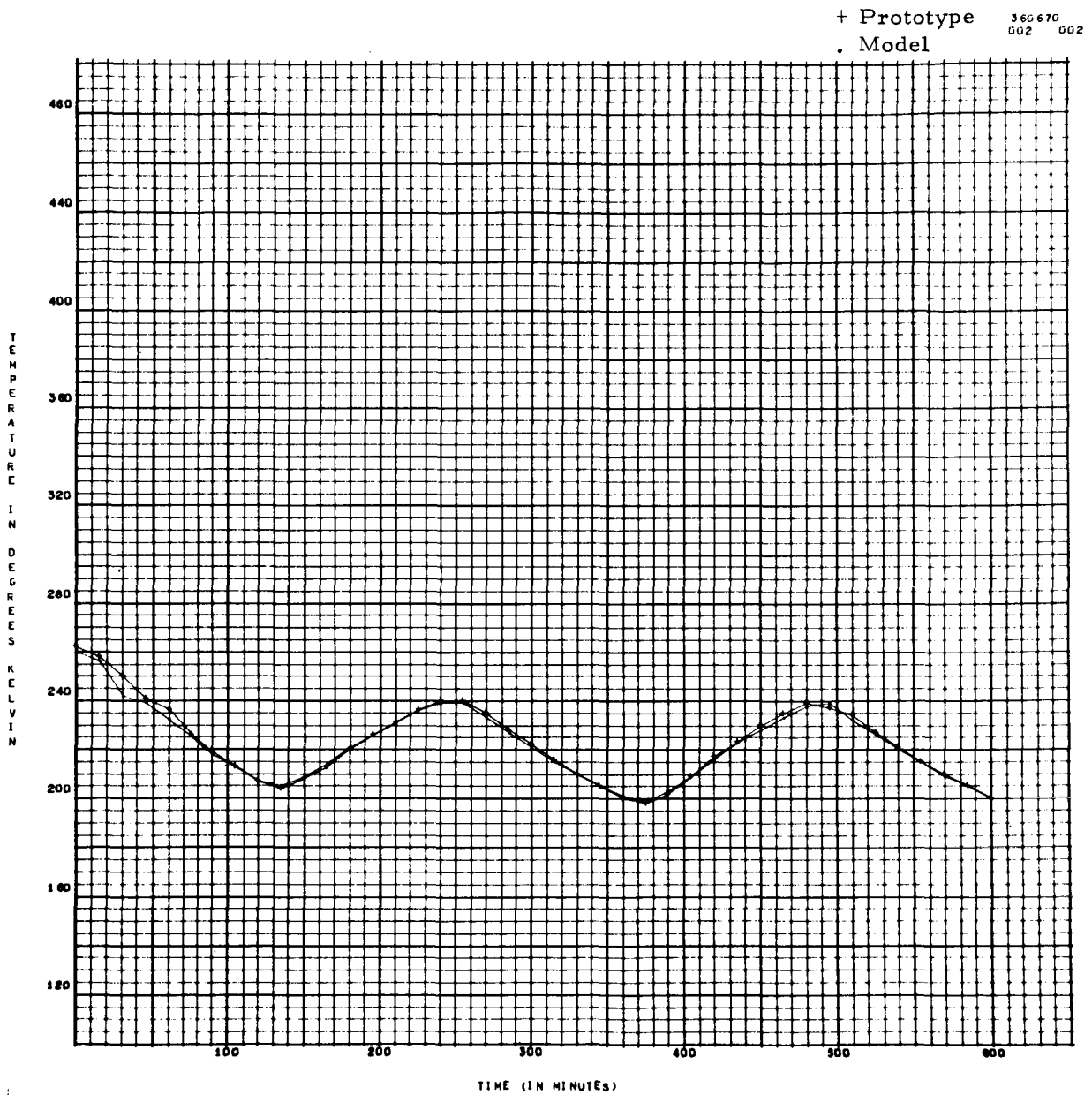


Figure 11 - Temperature-Time, Prototype and Model Cylinder, Thermocouple No. 22 (First Experiment)

+ Prototype  
• Model

360670  
008 008

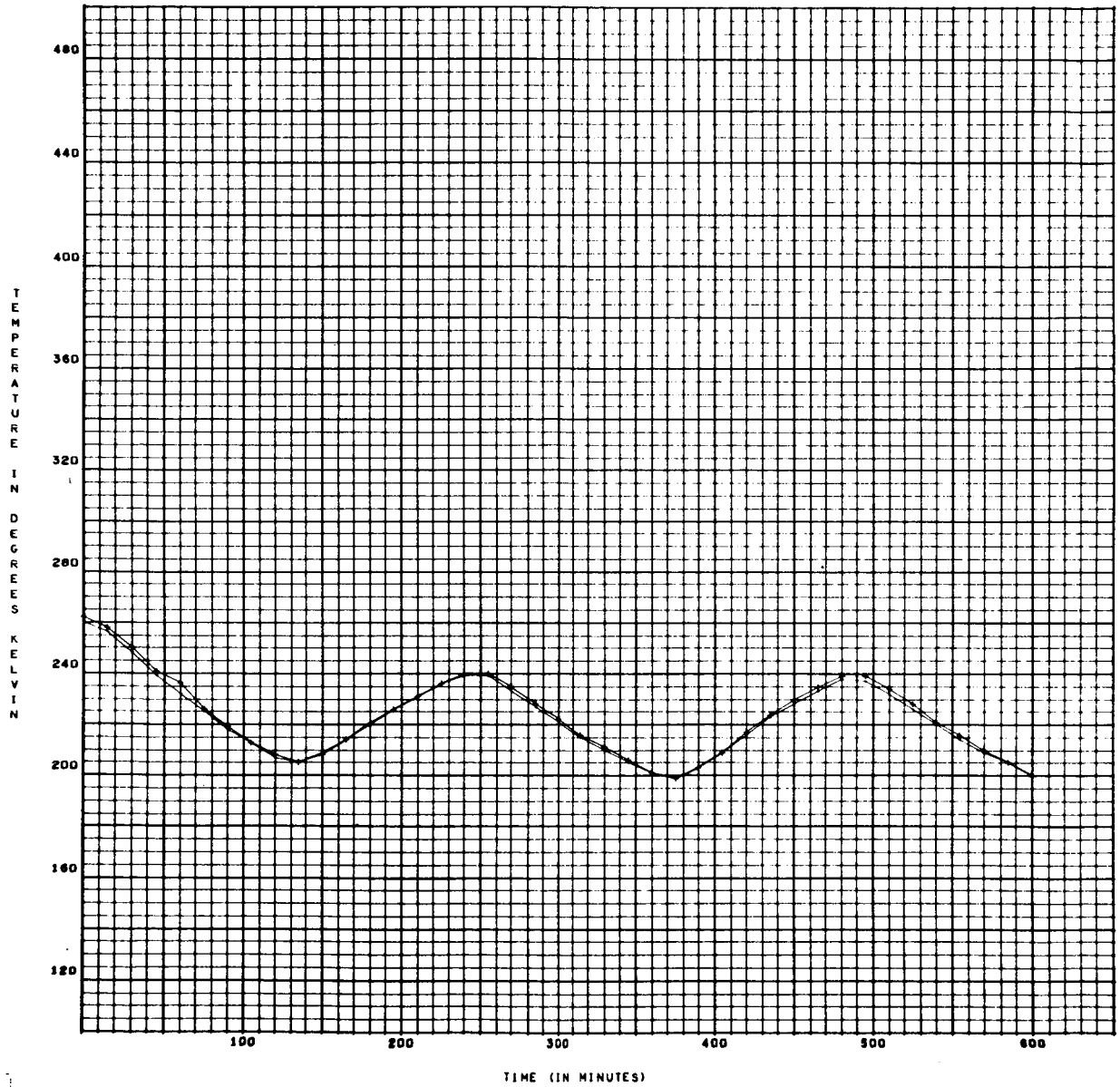


Figure 12 - Temperature-Time, Prototype and Model Cylinder, Thermocouple No. 24 (First Experiment)



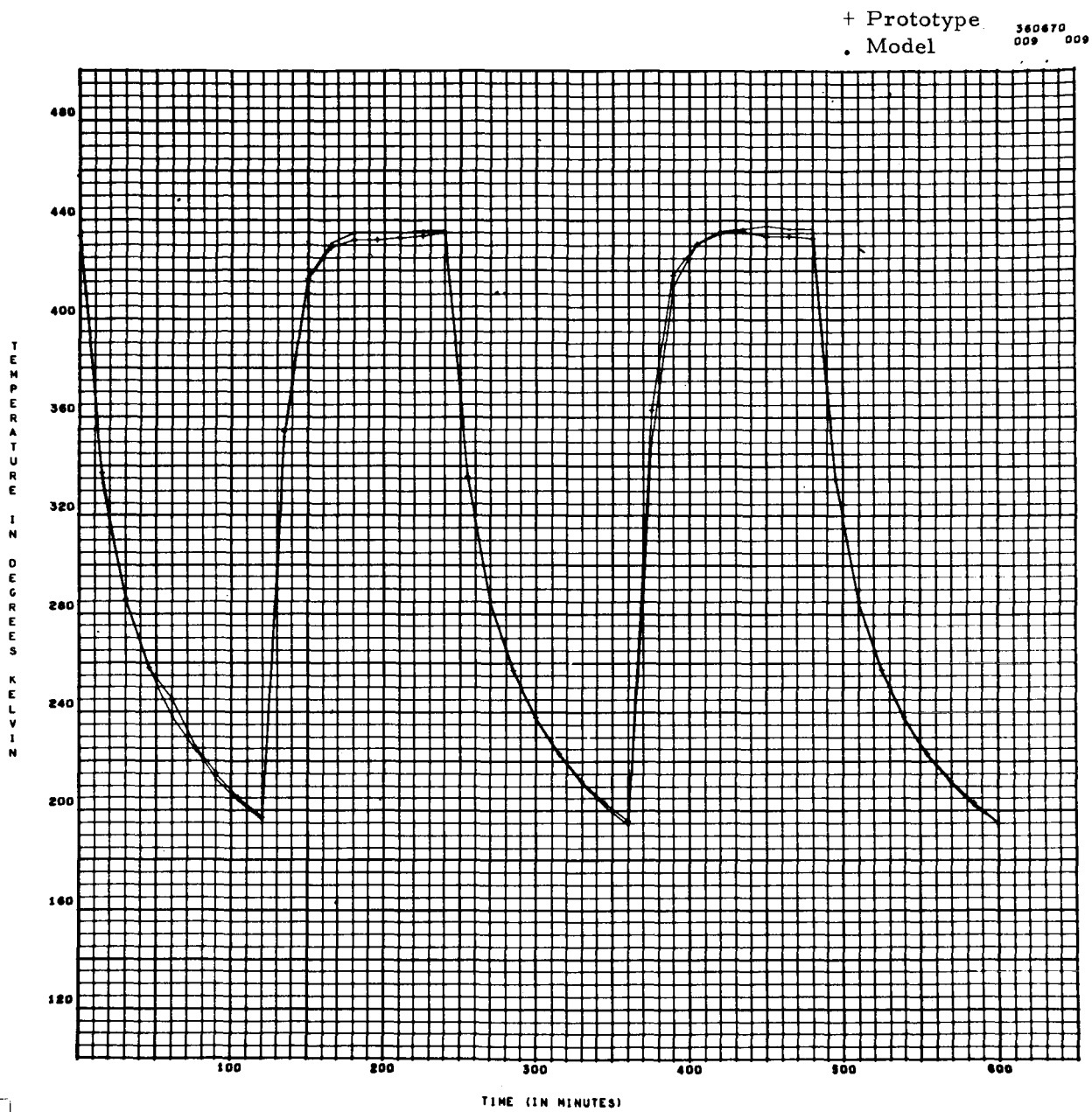


Figure 13 - Temperature-Time, Prototype and Model Plate, Thermocouple No. 25 (First Experiment)

+ Prototype  
• Model

360670  
010 010

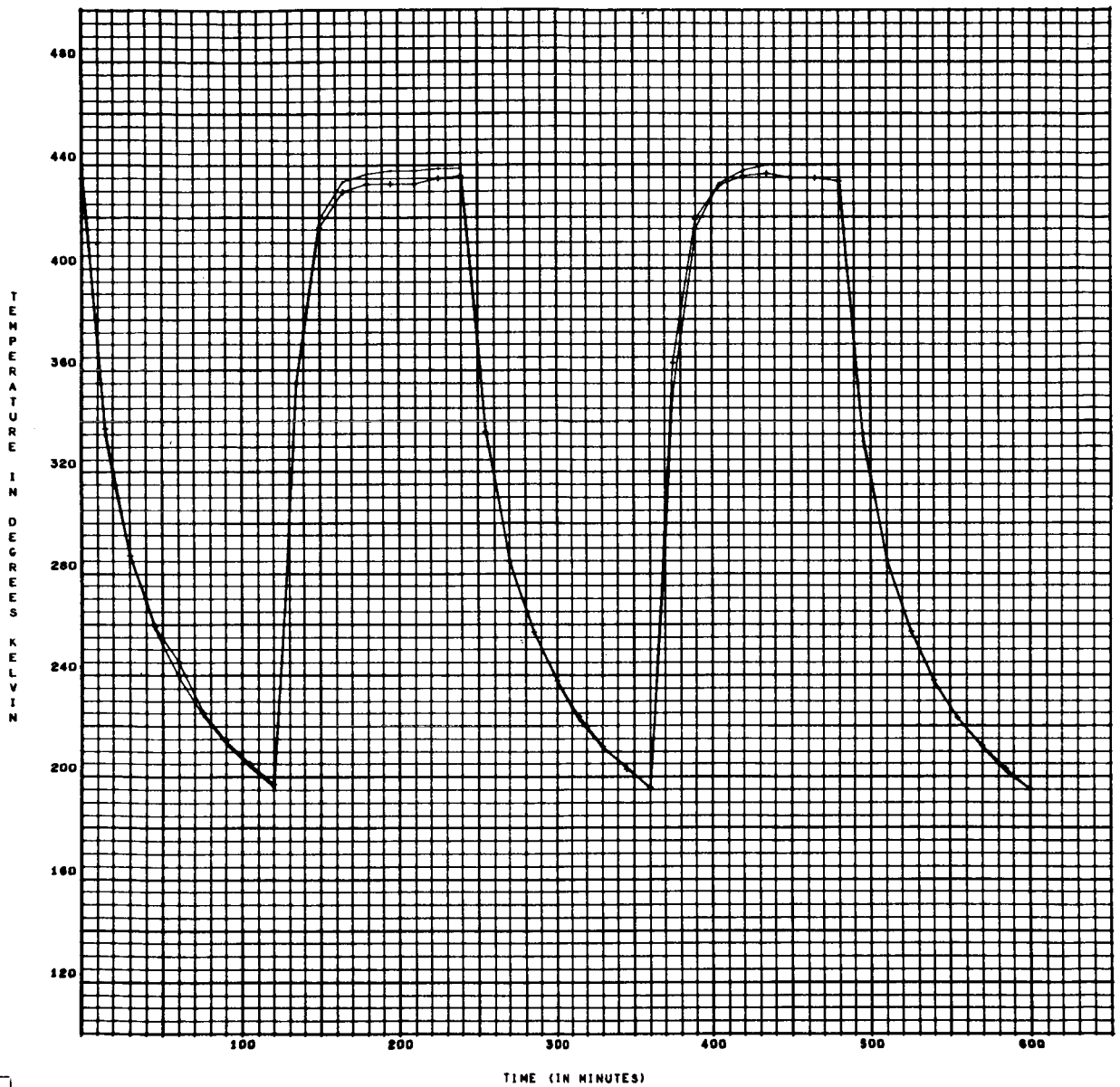


Figure 14 - Temperature-Time, Prototype and Model Plate, Thermocouple No. 27 (First Experiment)

+ Prototype  
• Model

360670  
011 011

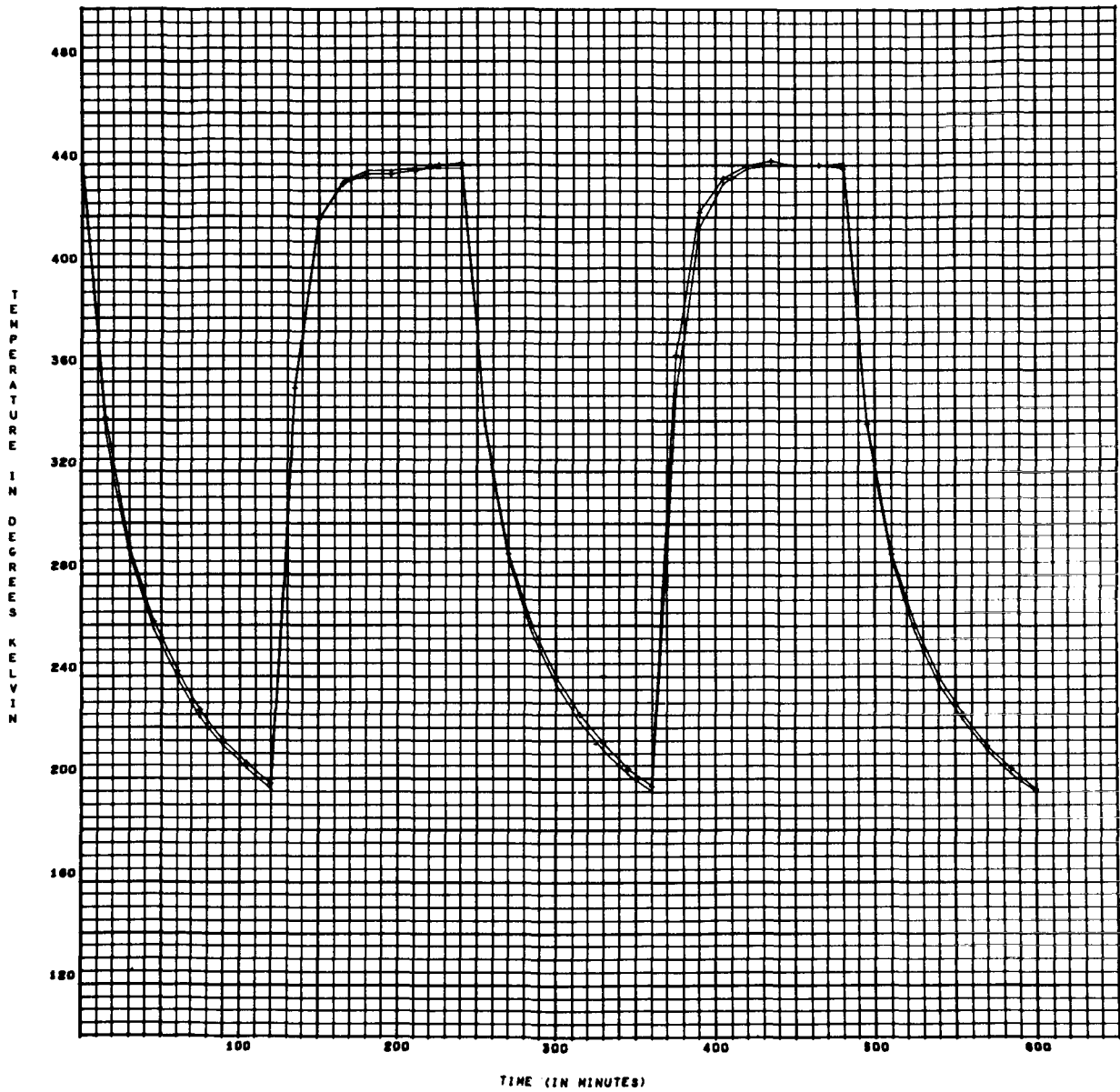


Figure 15 - Temperature-Time, Prototype and Model Plate, Thermocouple No. 29 (First Experiment)

+ Prototype  
• Model

360670  
012 012

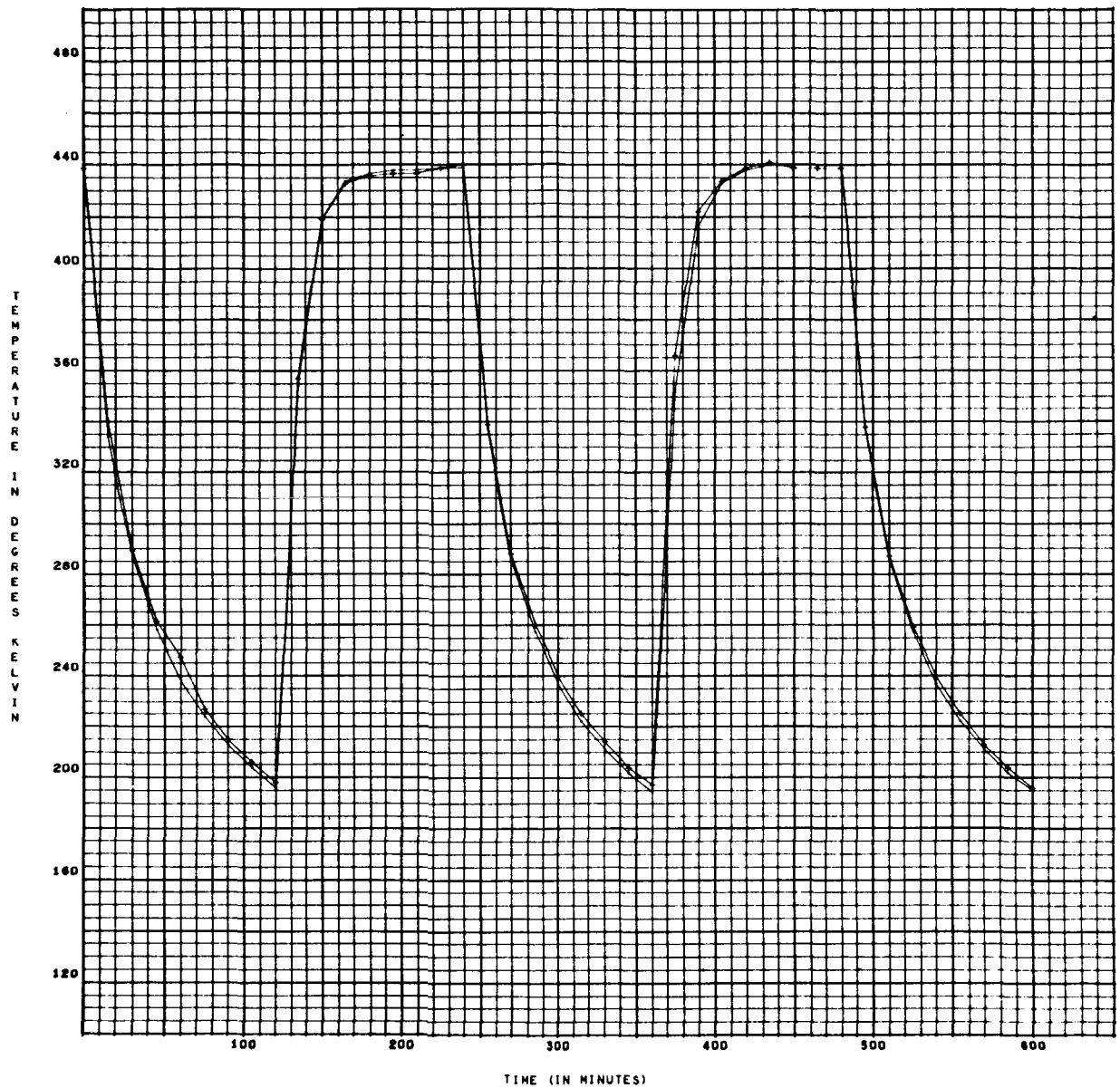


Figure 16 - Temperature-Time, Prototype and Model Plate, Thermocouple No. 32 (First Experiment)

+ Prototype  
. Model

360670  
001 001

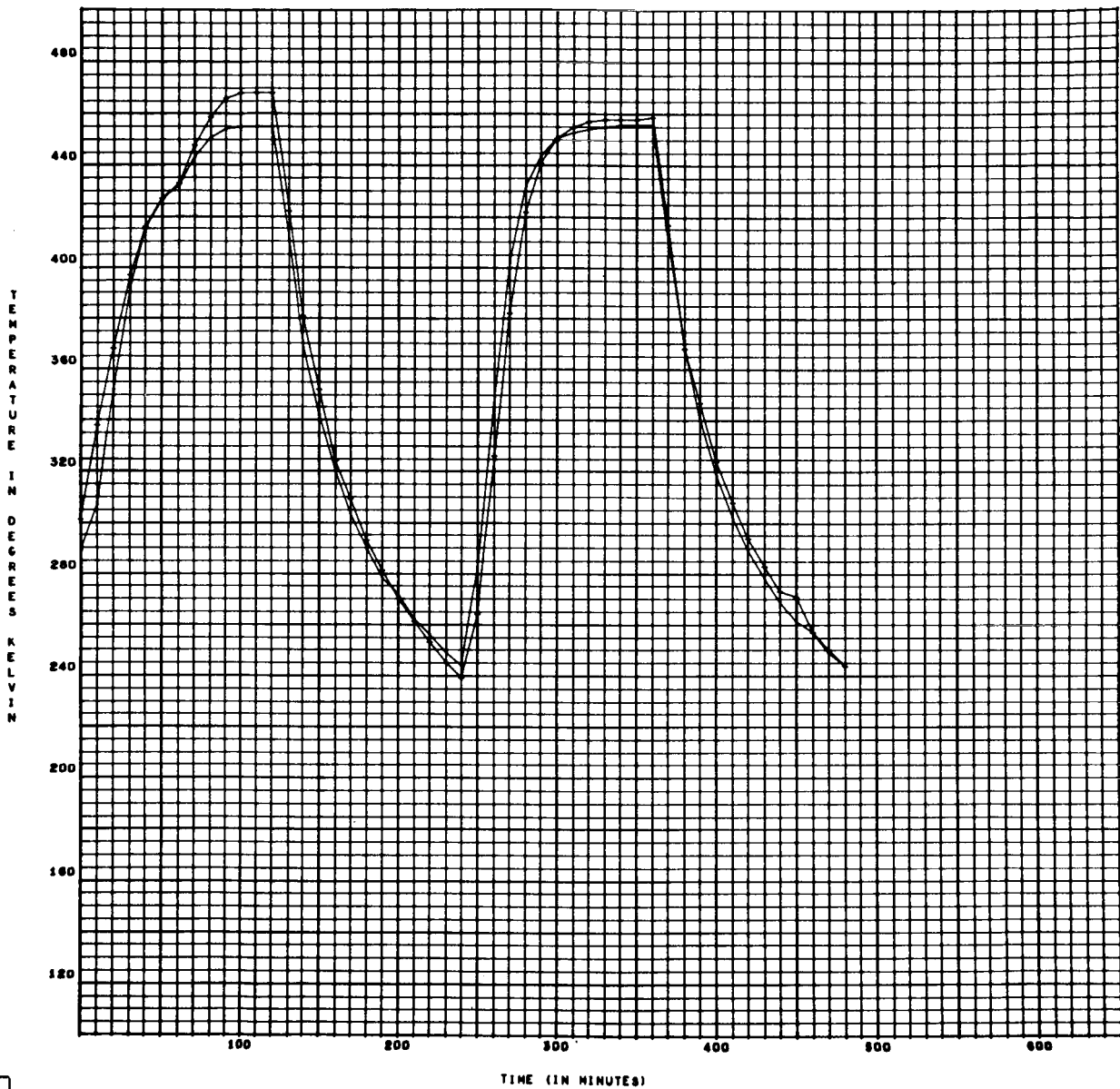


Figure 17 - Temperature-Time, Prototype and Model Sphere, Thermocouple No. 1 (Second Experiment)

+ Prototype  
. Model

360670  
002 002

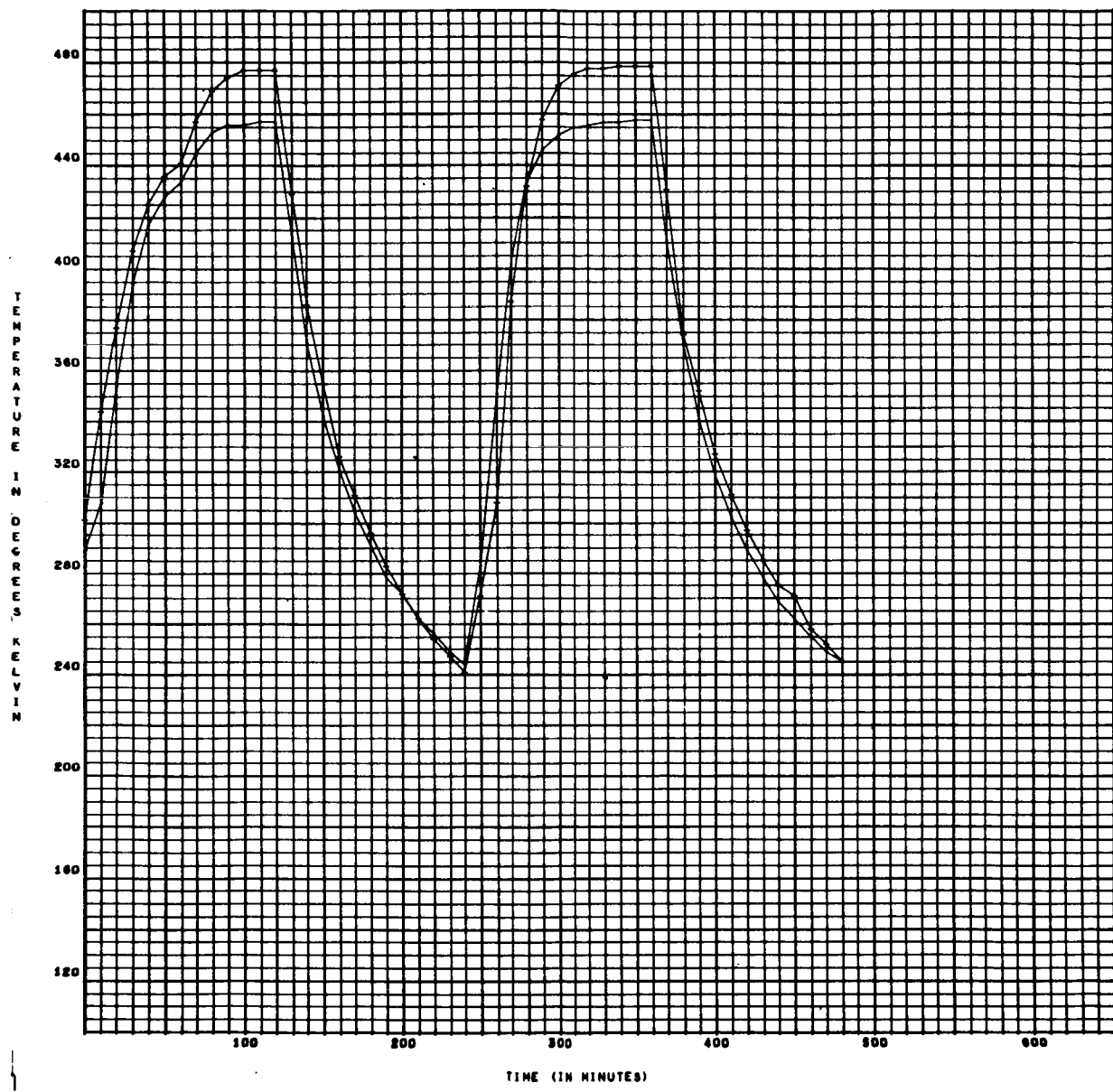


Figure 18 - Temperature-Time, Prototype and Model Sphere, Thermocouple No. 2 (Second Experiment)

+ Prototype  
• Model

360670  
003 003

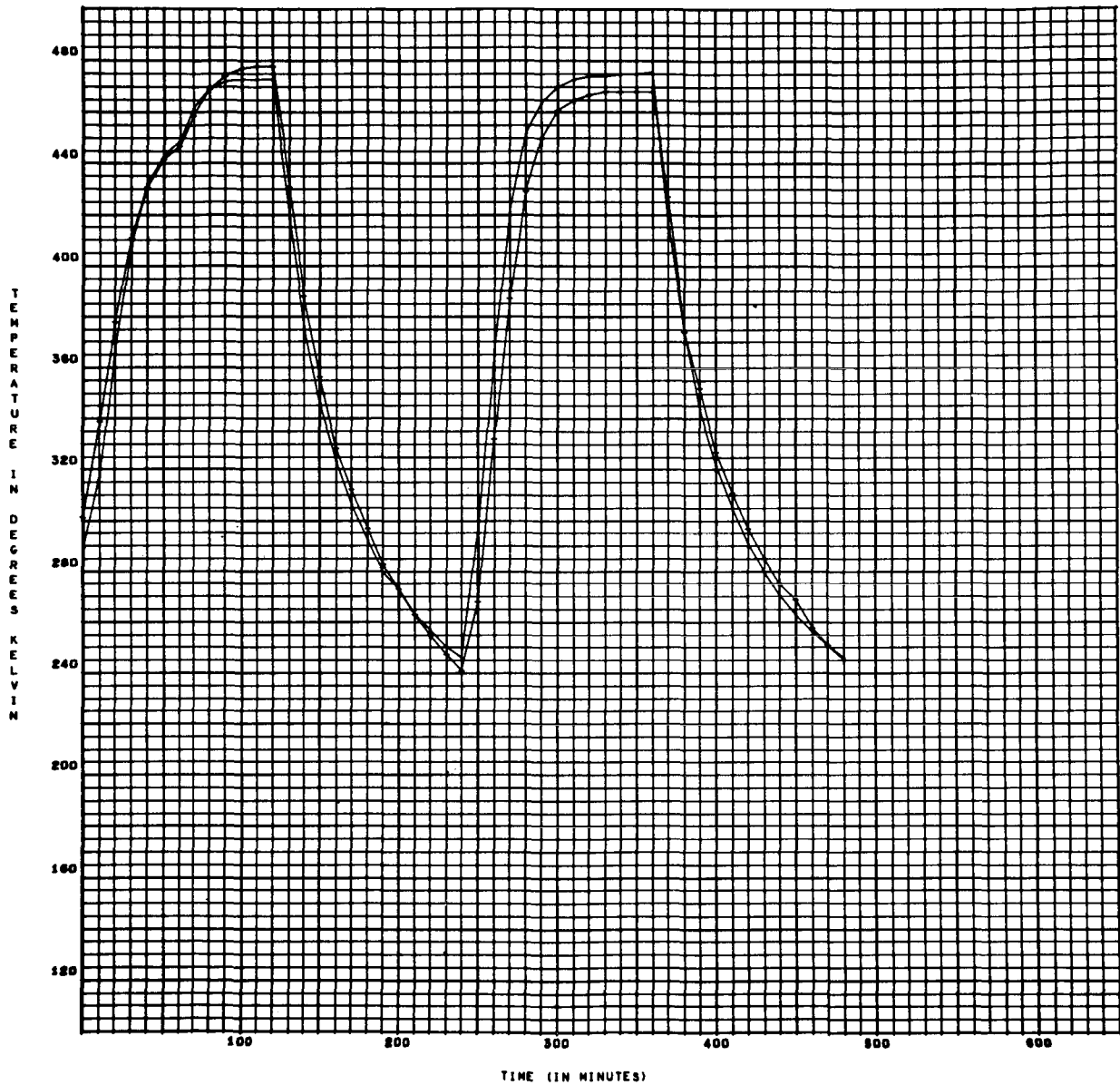


Figure 19 - Temperature-Time, Prototype and Sphere, Thermocouple No. 3 (Second Experiment)

+ Prototype  
 . Model

360870  
 004 004

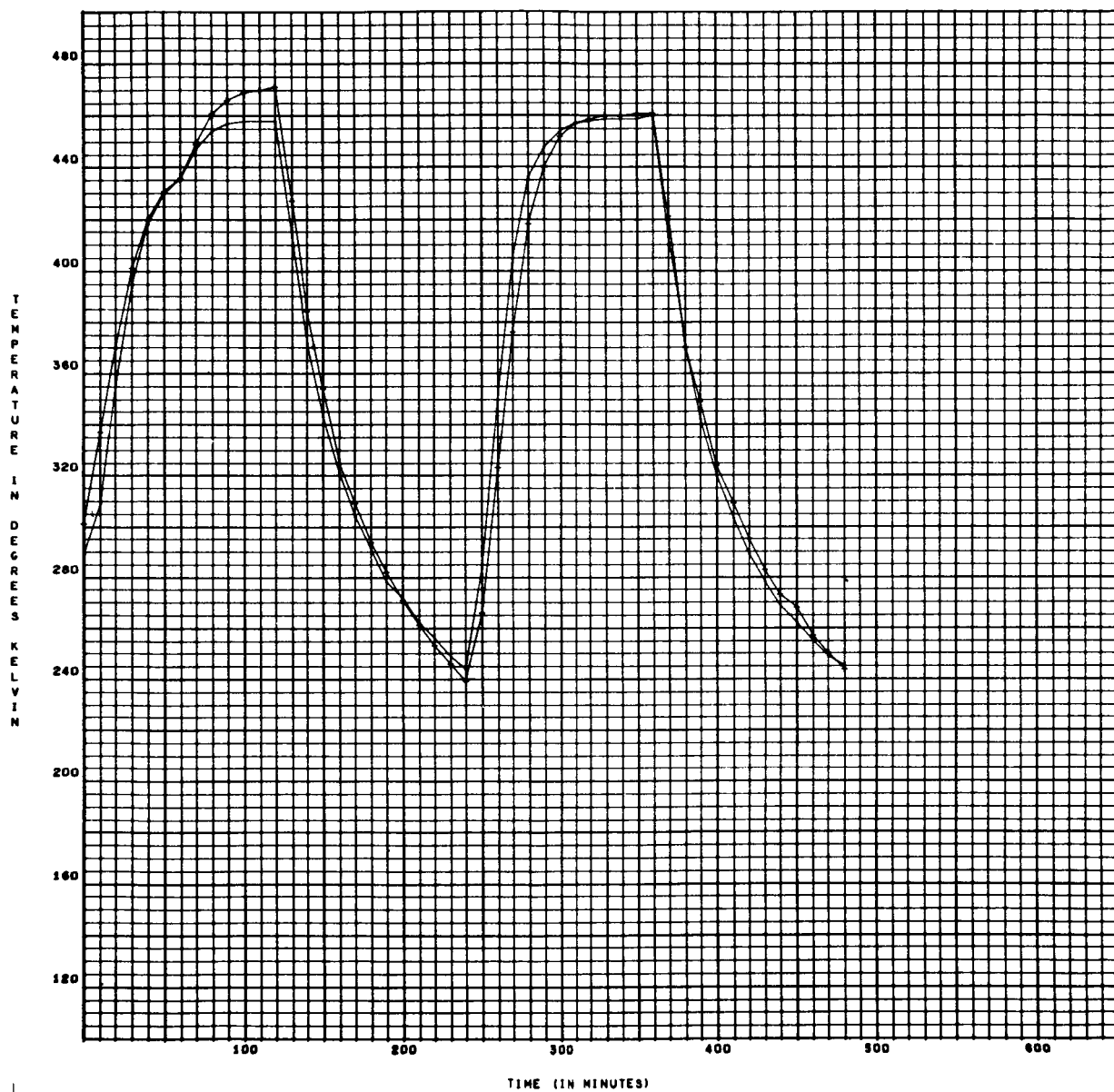


Figure 20 - Temperature-Time, Prototype and Model Sphere, Thermocouple No. 4 (Second Experiment)



+ Prototype  
• Model

360670  
005 005

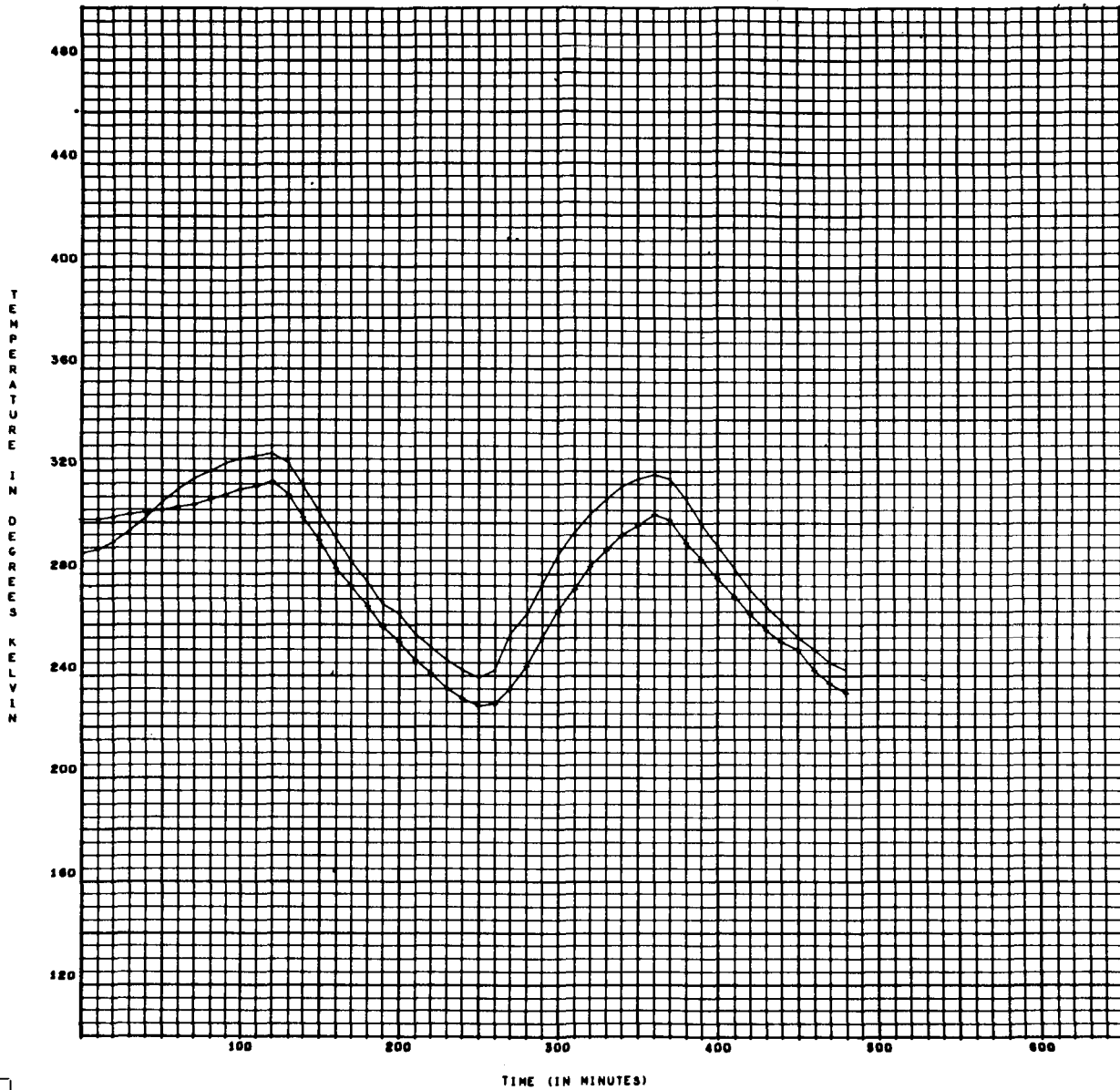


Figure 21 - Temperature-Time, Prototype and Model Cylinder, Thermocouple No. 16 (Second Experiment)

+ Prototype  
. Model

360670  
006 006

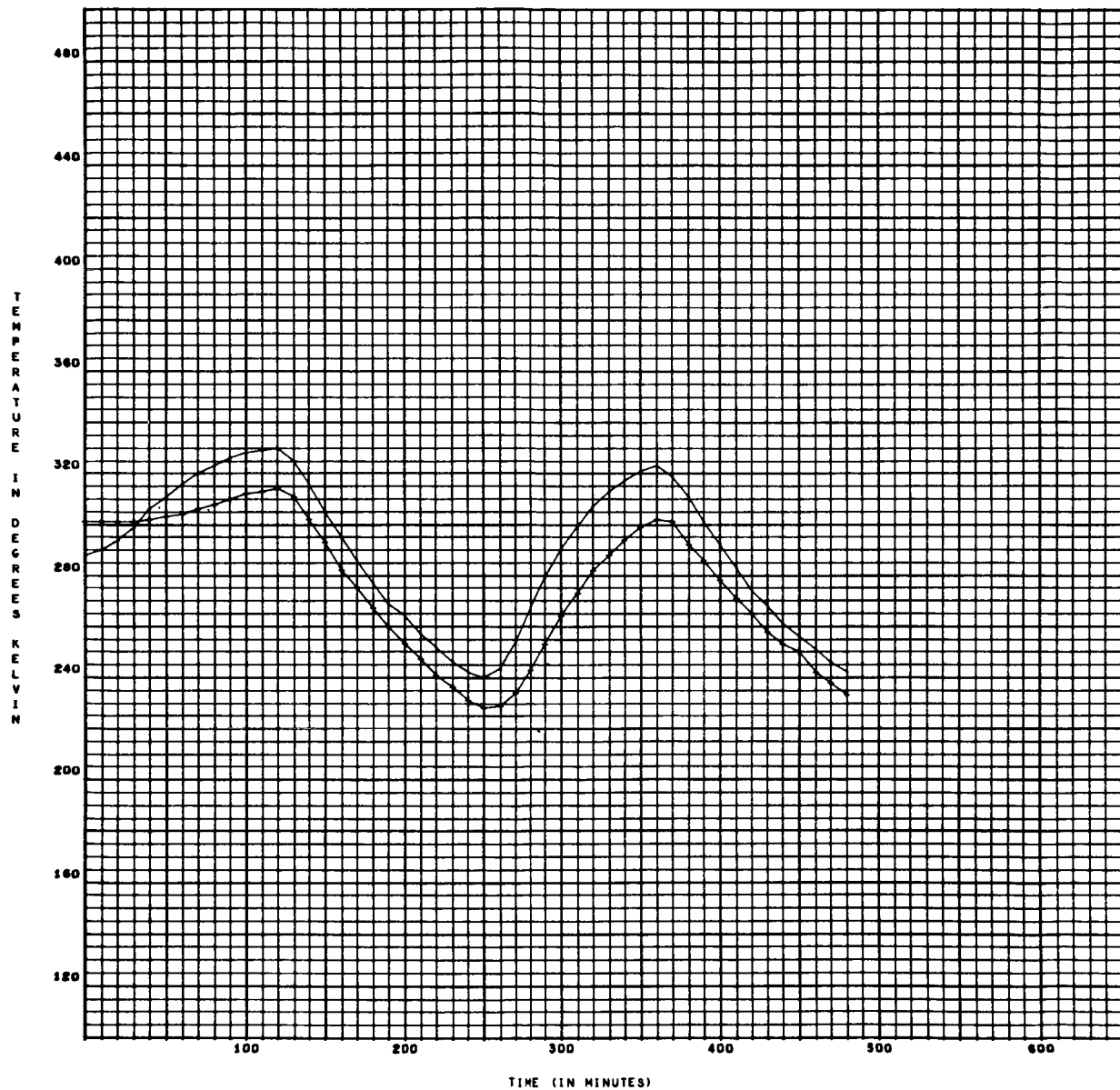


Figure 22 - Temperature-Time, Prototype and Model Cylinder, Thermocouple No. 17 (Second Experiment)

+ Prototype  
· Model

360870  
007 007

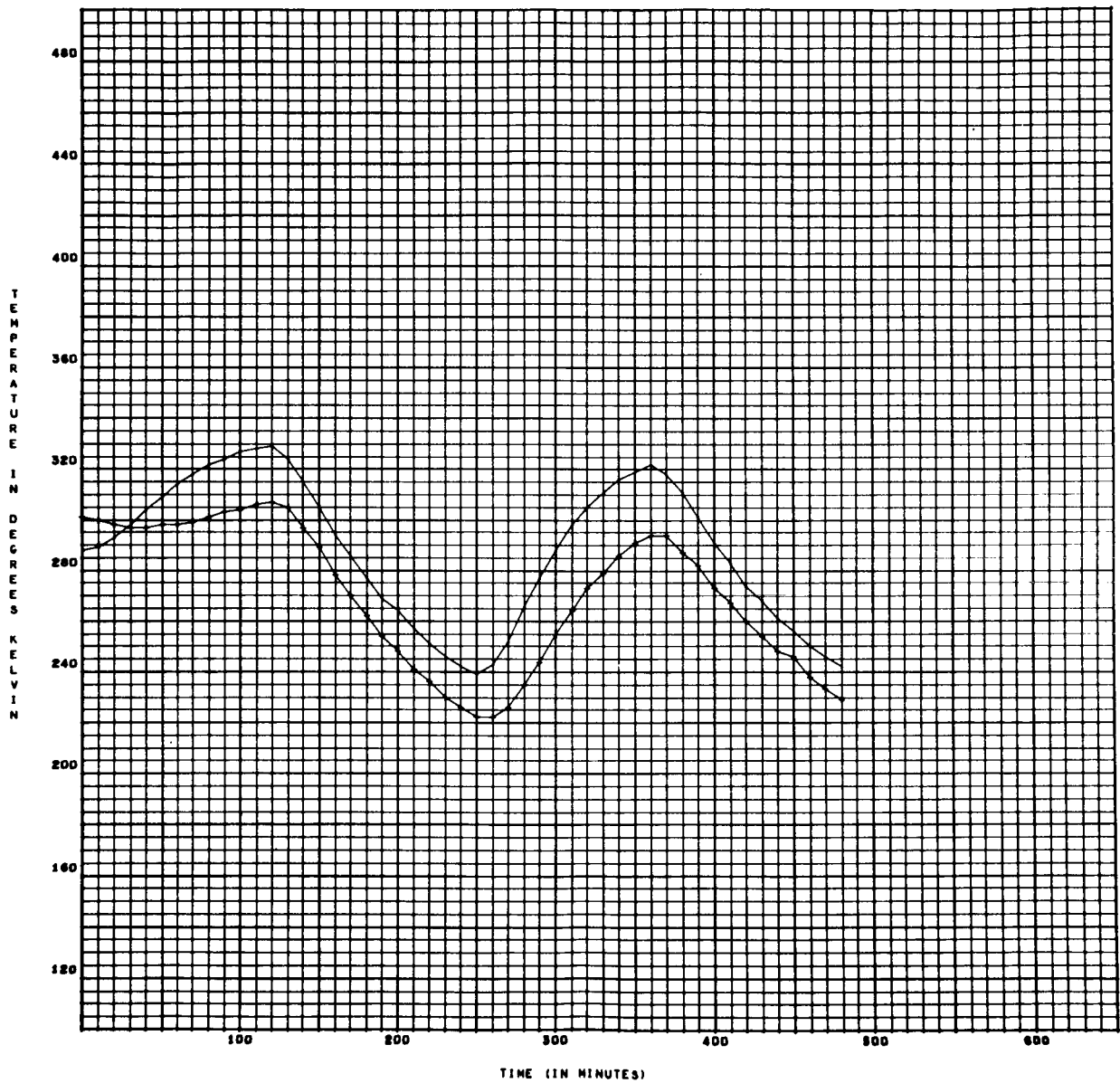


Figure 23 - Temperature-Time, Prototype and Model Cylinder, Thermocouple No. 18 (Second Experiment)

+ Prototype  
. Model

360670  
000 000

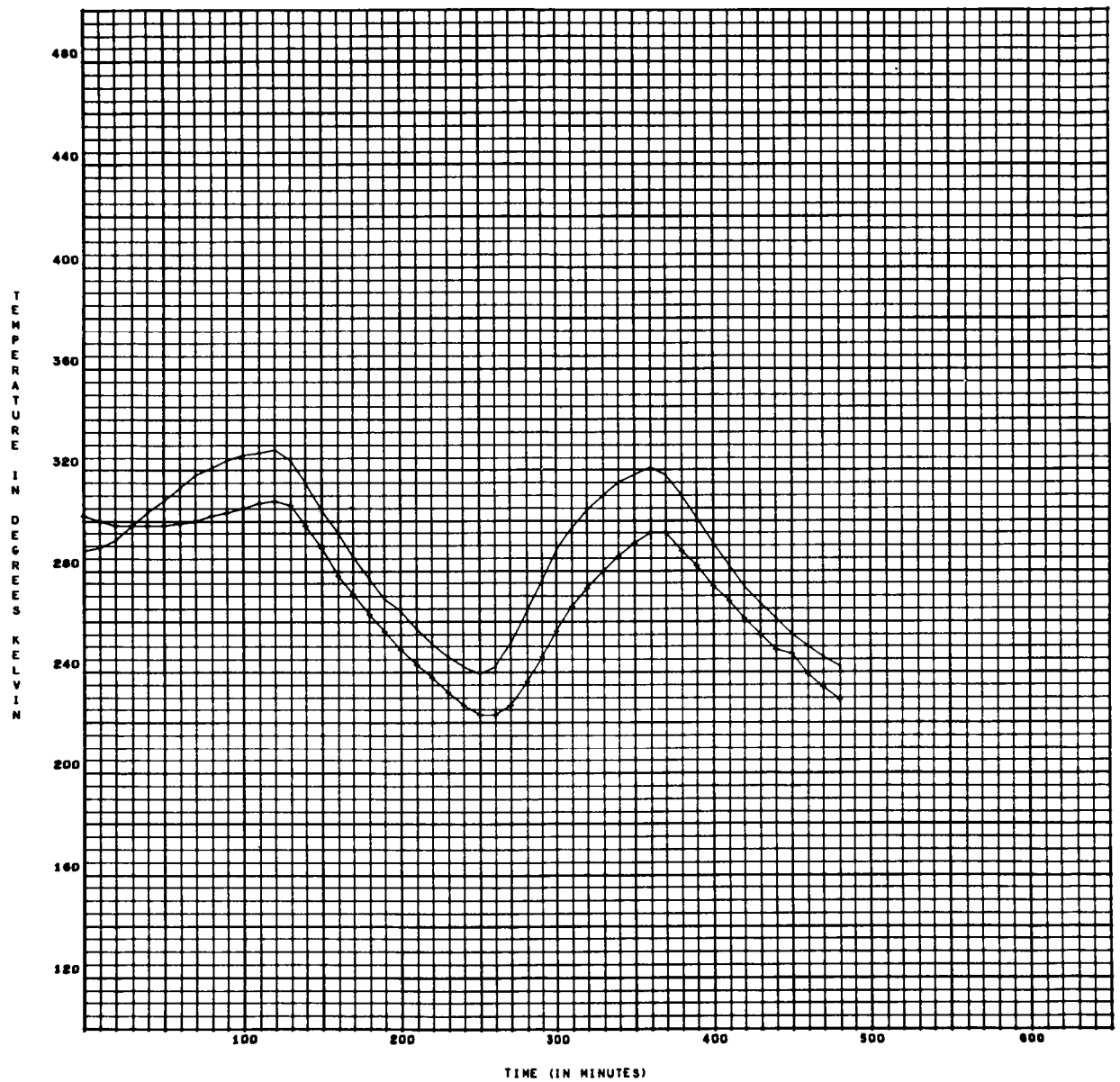


Figure 24 - Temperature-Time, Prototype and Model Cylinder, Thermocouple No. 19 (Second Experiment)

+ Prototype  
• Model

380670  
009 009

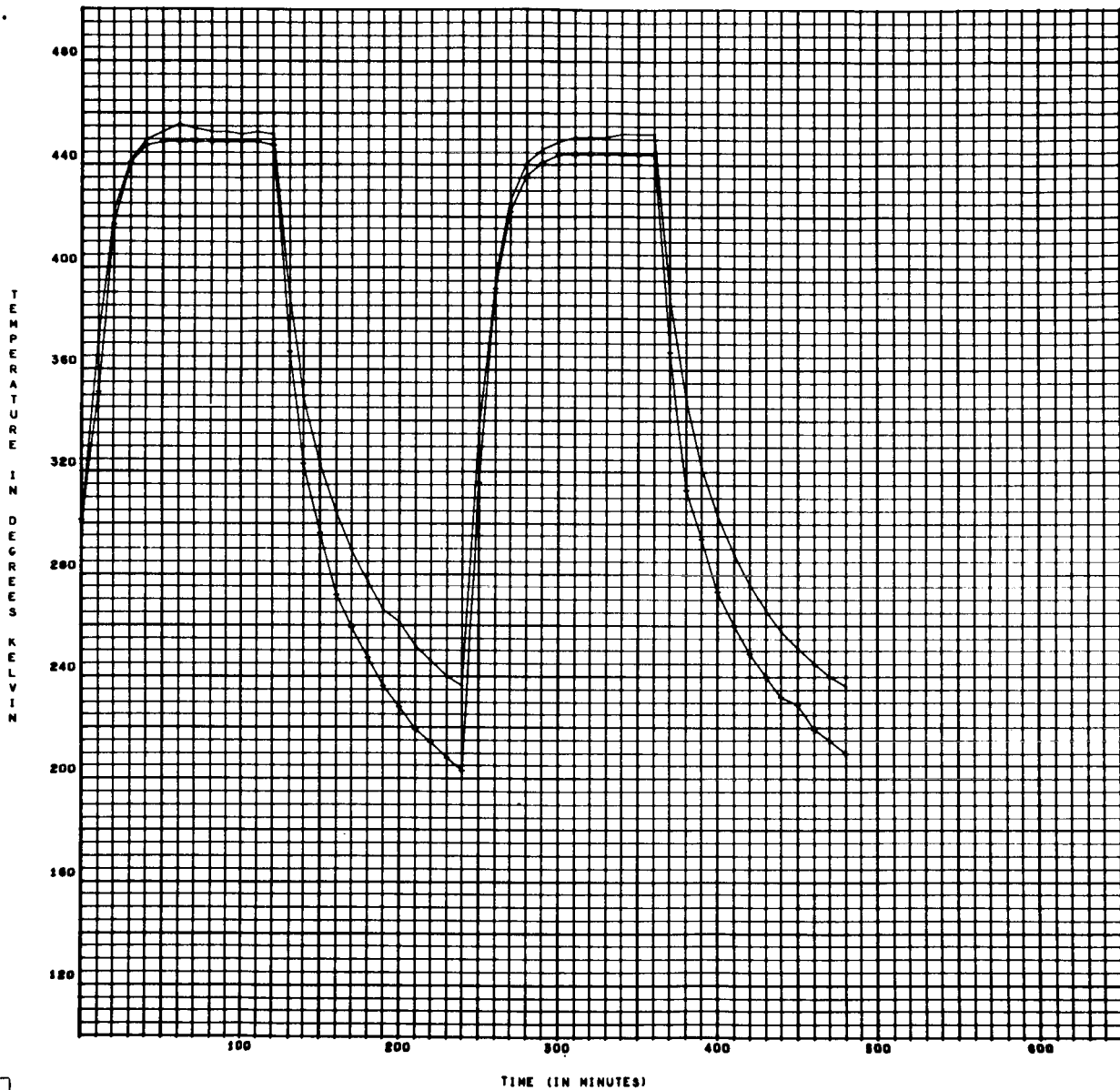


Figure 25 - Temperature-Time, Prototype and Model Plate, Thermocouple No. 20 (Second Experiment)

+ Prototype  
 . Model

360670  
 010 010

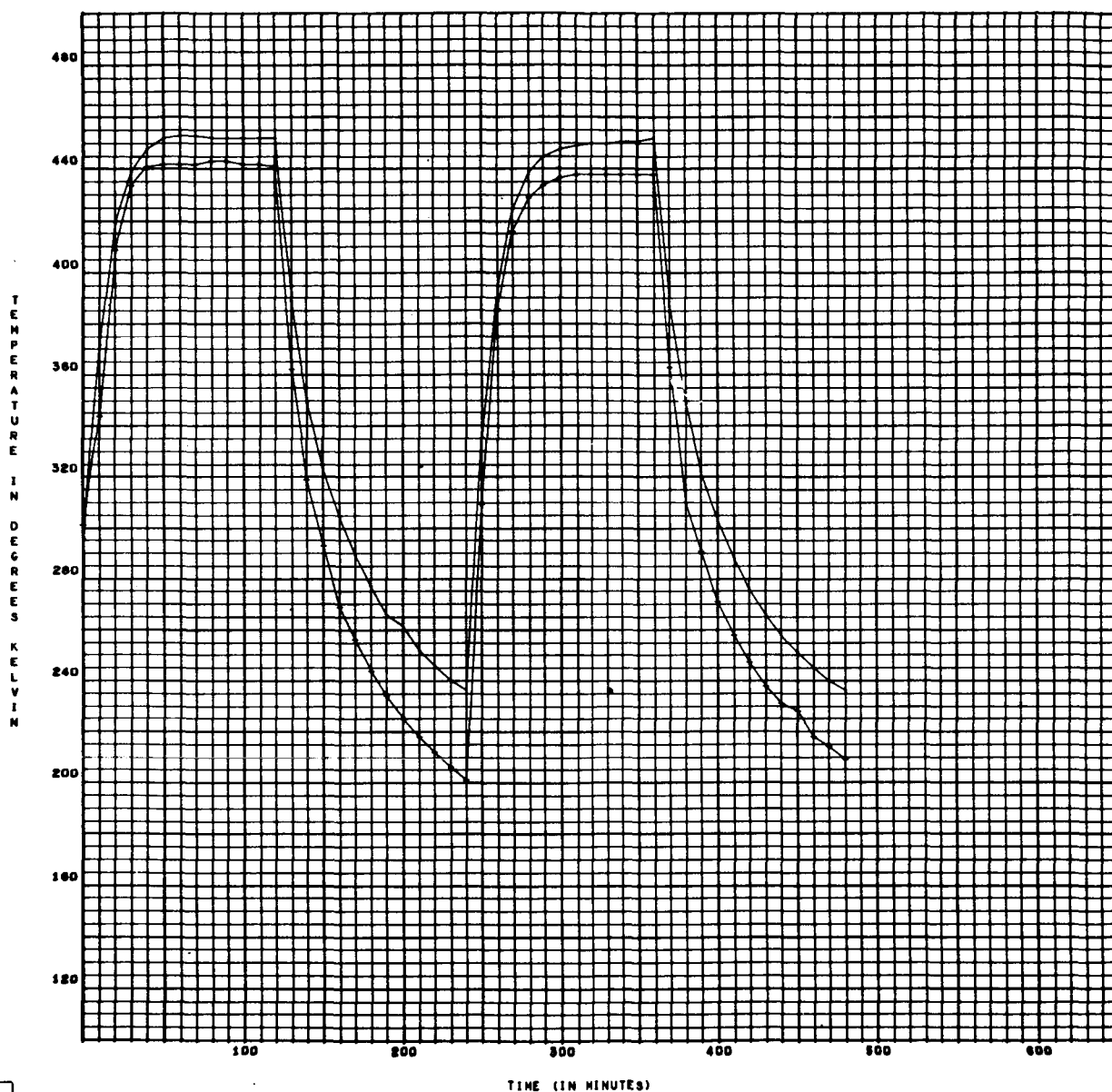


Figure 26 - Temperature-Time, Prototype and Model Plate, Thermocouple No. 22 (Second Experiment)

+ Prototype  
• Model

360670  
011 011

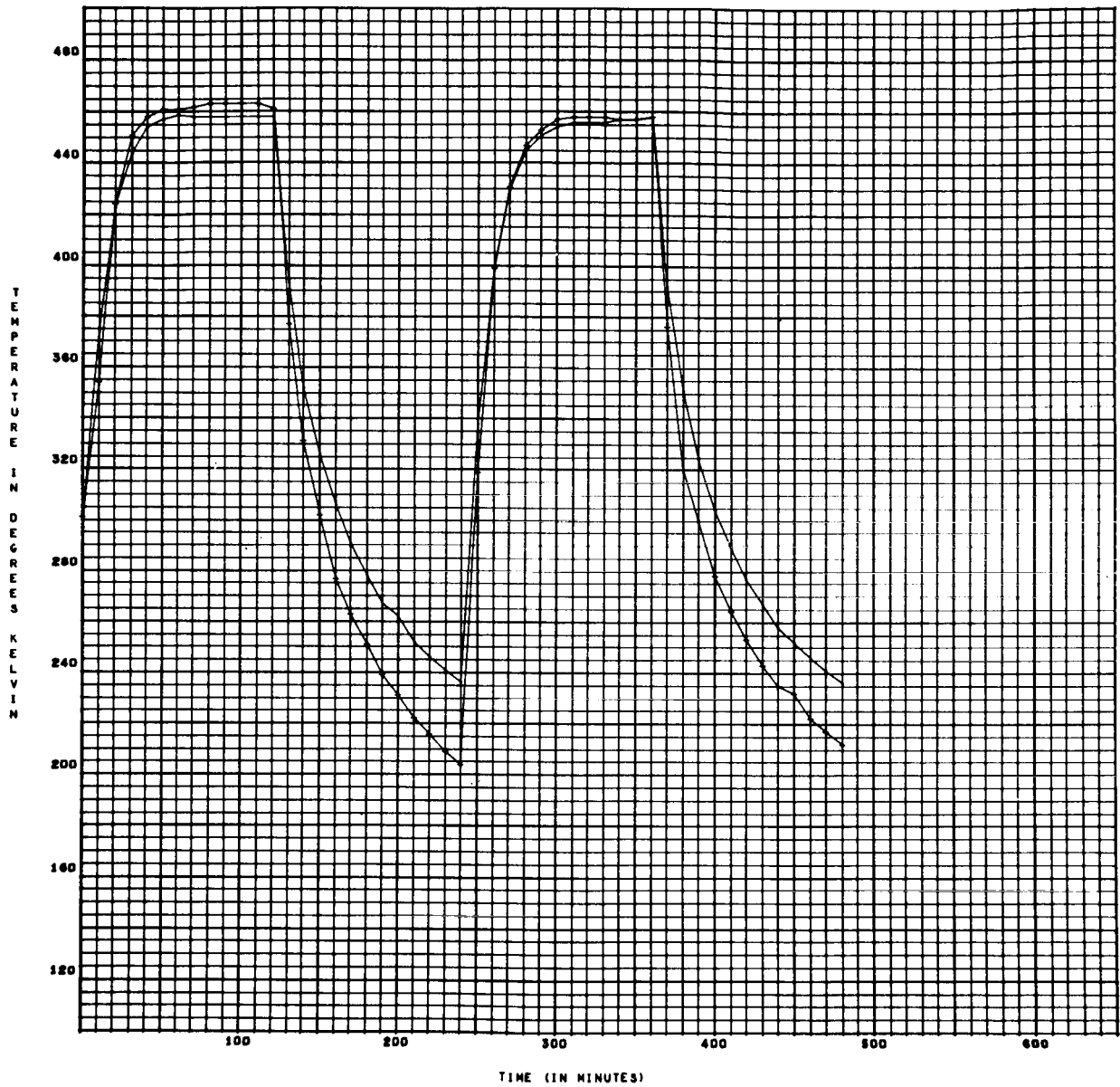


Figure 27 - Temperature-Time, Prototype and Model Plate, Thermocouple No. 24 (Second Experiment)

+ Prototype  
· Model

360670  
012 012

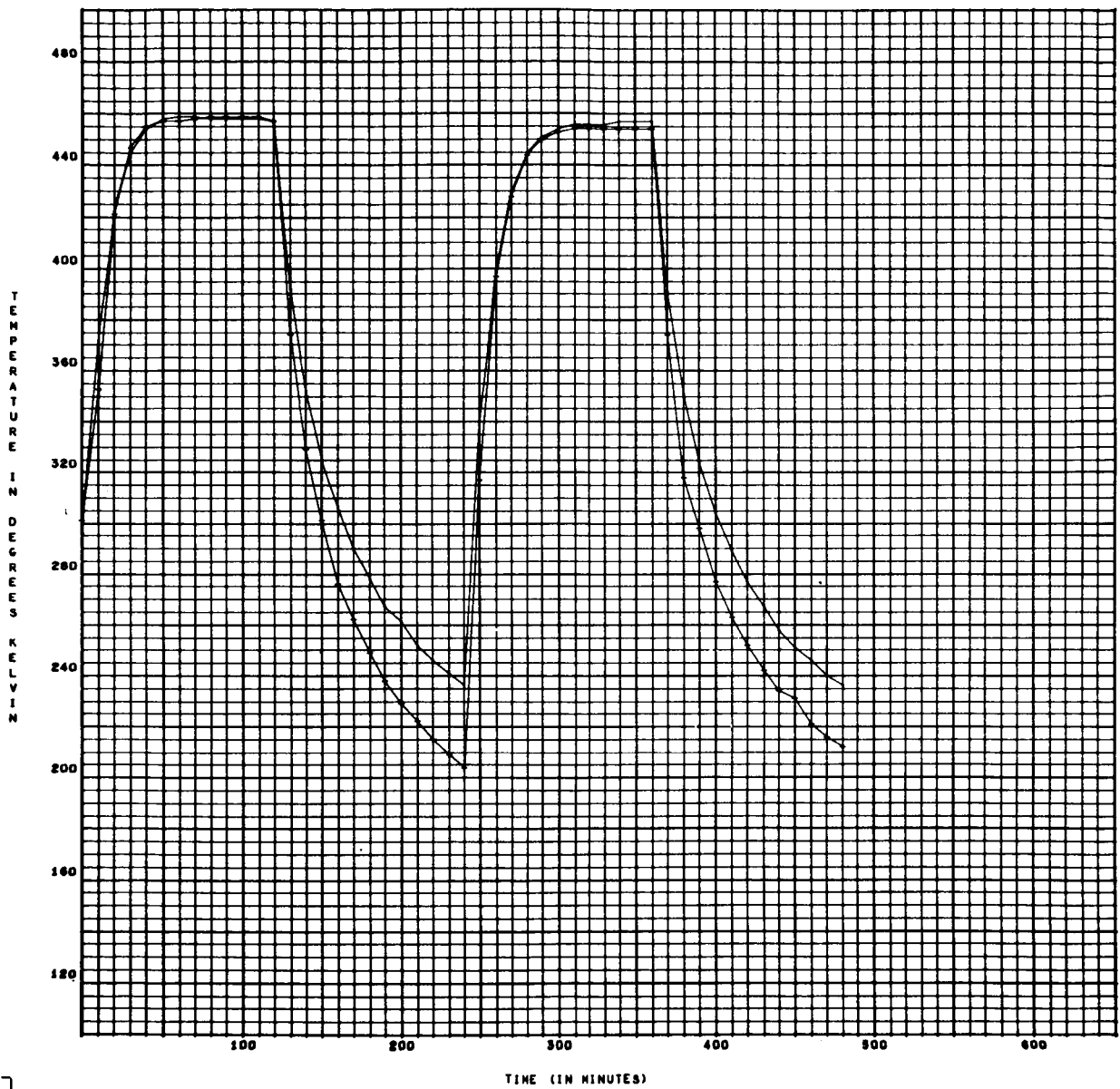


Figure 28 - Temperature-Time, Prototype and Model Plate, Thermocouple No. 25 (Second Experiment)



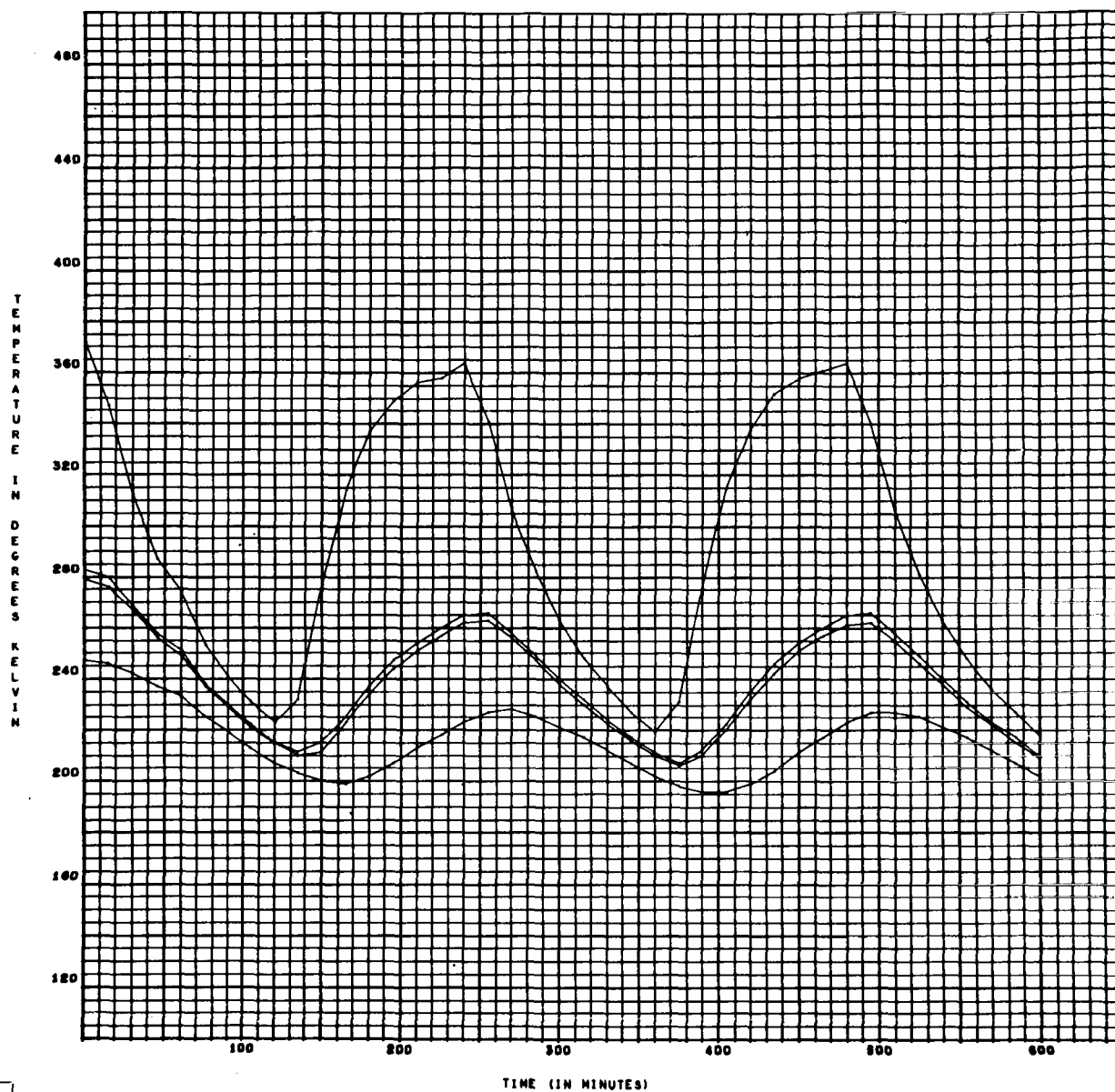


Figure 29 - Temperatures for Prototype Sphere for First Experiment

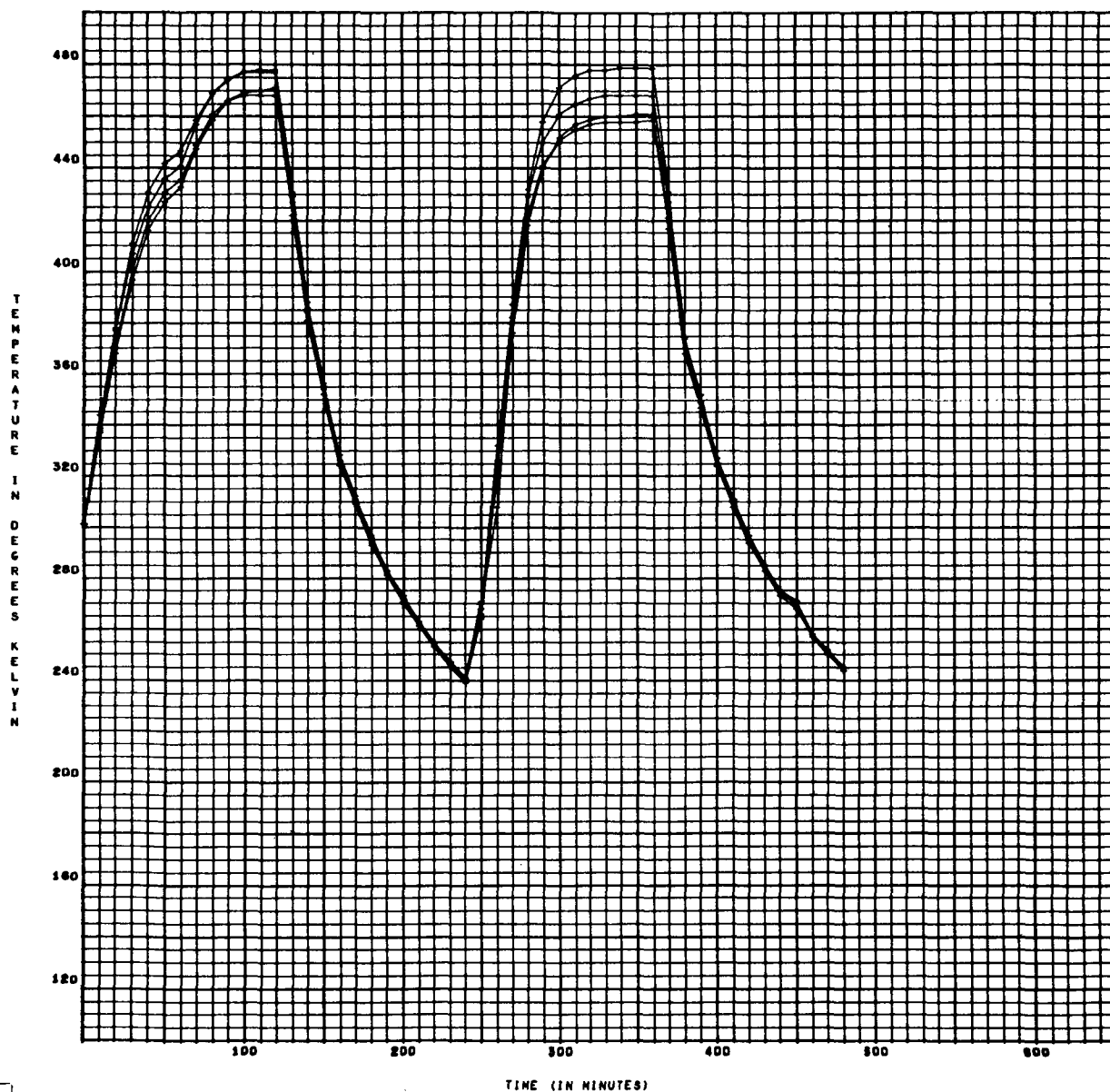


Figure 30 - Temperatures for Prototype Sphere for Second Experiment

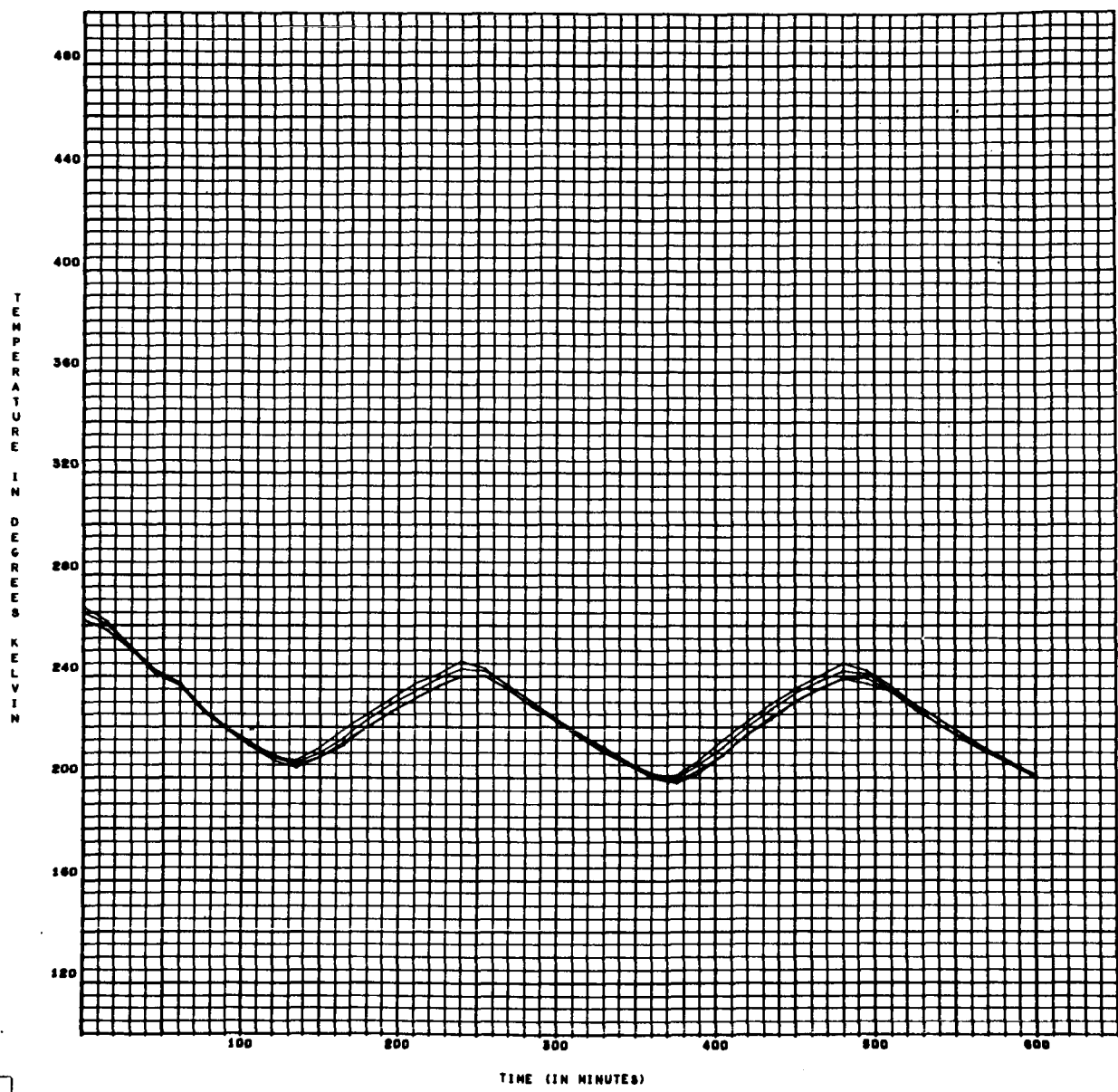


Figure 31 - Temperatures for Prototype Cylinder for First Experiment

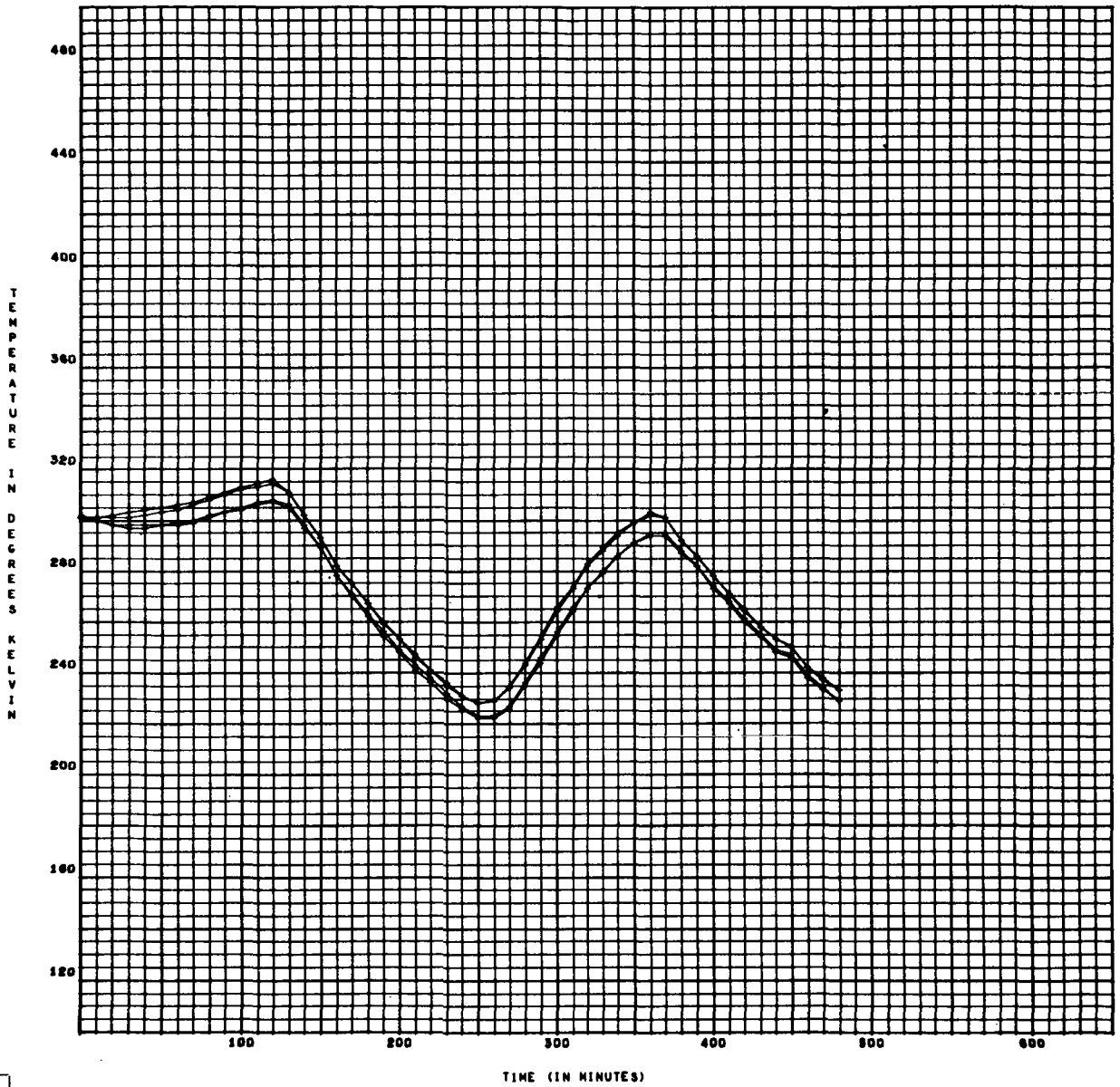


Figure 32 - Temperatures for Prototype Cylinder for Second Experiment

October 18, 1965

APPROVAL

TMX-53346

A SET OF EXPERIMENTS IN  
THERMAL SIMILITUDE

by

Billy P. Jones

and

James K. Harrison

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

A handwritten signature in cursive script that reads "Gerhard B. Heller". The signature is written in dark ink and is positioned above a horizontal line.

GERHARD B. HELLER

Dep. Director, Research Projects Laboratory

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